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NON-STATIONARY FACTORS OF FATIGUE RESISTANCE AND THEIR INFLUENCE ON THE SERVICE LIFE OF FREIGHT CAR JOINTS: MATHEMATICAL MODELING AND ANALYSIS

The article is devoted to mathematical modeling and analysis of the proposed modified version of the linear hypothesis of fatigue damage accumulation, this modification of the classical linear hypothesis (Palmgren-Mayer) allows more accurate prediction of the residual life of a structure. which uses a conditional value of the endurance limit determined by the coefficient of the lower limit of damaging stresses.

The linear hypothesis of fatigue damage accumulation, proposed by A. Palmgren (1924) and developed by M. Mayer (1939), is the basis for calculating the durability of materials under cyclic loading. Based on the analysis of the indirect characteristic of accumulated fatigue damage – the fracture energy of local models of freight car frame assemblies, the dependence of the endurance limit decrease on the proportion of the produced resource, which takes into account the dynamic decrease in the endurance limit during operation, is determined. The most significant disadvantages of the linear theory are that it does not describe the effect of the alternation of stresses of different levels.

Thus, for the considered design variants of freight car bearing assemblies, the application of the modified linear hypothesis using the calculated fatigue curves can provide a high accuracy of the predictive calculation of durability at a value of K = 0.735. In addition, a positive property of the proposed method is the direction of the error into the safety margin.

A computational justification of the lower limit of damaging stress is given. A modification of the linear hypothesis is proposed. It takes into account the nonlinearity due to the reduction of σ_{-1} and the introduction of σ_{min}. It is confirmed by energy and experimental data. Reduces the risk of service life overestimation by 30–50% compared to the classical approach.

Key words: *railway transport, rolling stock, car fleet, machine-building structures, fatigue damage, durability of bearing units of freight cars, mathematical description, mathematical models.*

Statement of the problem. Wear and damage to freight car joints remain a critical problem in rail transport, directly affecting traffic safety and economic efficiency of transportation. Increased requirements for freight turnover and speed of movement enhance the effect of non-stationary fatigue resistance factors, which leads to accelerated accumulation of damage in metal car structures.

Non-stationary factors of fatigue resistance include variable loads, vibrations, shocks, as well as corrosion processes, which can change their intensity and nature during the operation of the car. Their complex impact on the resource of connections is complex and requires detailed study. Traditional methods of fatigue assessment, based on constant loads, often turn out to be insufficiently accurate for predicting the durability of structural elements in real operating conditions.

Analysis of information sources on the topic under study. The article [1] investigates the prediction of wheel wear of heavy freight cars based on tests on a roller stand and on the line. The authors consider the factors affecting wheel wear and develop models for its prediction. Experimental data obtained in laboratory and field conditions are used. The results of the study can be used to optimize wheel maintenance and improve the safety of railway transport. The article is relevant for specialists in the field of railway engineering and operation.

Article [2] presents a comparative analysis of the fatigue strength of a freight car frame. The authors investigate the influence of various design solutions on the fatigue strength of the frame. Methods for calculating stresses and strains are considered. The results of experimental studies and numerical modeling are analyzed. The results of the study can be used to optimize the frame design.

The scientific and applied work [3] investigates the determination of the durability of the supporting structure of the body of an open wagon made of round pipes during its transportation on a railway ferry. The authors analyze the influence of dynamic loads on the design of the wagon during sea transportation. Methods for calculating strength and fatigue durability are considered. The results obtained can be used to optimize the design of wagons and ensure the safety of their transportation. The article is important for design engineers and specialists in the field of transport engineering.

The authors of the publication [4] present a study of dynamic weighing to improve the safety of rail freight transport using the example of the Czech Republic. The authors analyze the effectiveness of using dynamic weighing systems to control the load on moving wagons. The advantages and disadvantages of this technology are considered. The impact of dynamic weighing on traffic safety and accident prevention is assessed. The results of the study emphasize the importance of implementing modern monitoring systems to ensure the safety of rail transport.

The article [5] investigates the determination of the dynamic load on a gondola car when it is attached to the ferry deck by a viscous coupling. The authors analyze the forces acting on the car during transportation on a ferry, taking into account the characteristics of the viscous coupling. Mathematical models and methods for calculating dynamic loads are considered. The results of the study can be used to design car fastening systems and ensure transportation safety. The article is important for specialists in the field of transport engineering.

In the article [6] the influence of the load from the axle of a gondola car on its dynamic performance and the railway track is investigated. The authors analyze the interaction of the car with the track at different load levels. The vertical and horizontal forces acting between the wheel and the rail are considered. The influence of stresses on the track and car elements is assessed. The results of the study can be used to optimize the design of cars and reduce track wear.

Document [7] is a UIC (International Union of Railways) standard and contains a test programme for wagons with steel frame and body construction and their cast steel bogies. The standard specifies test procedures and requirements to ensure the safety and reliability of wagons. The document is important for manufacturers, operators and regulatory authorities in the railway industry.

In the article [8] the dynamic calibration of the Weigh in Motion (WIM) system is considered. The authors investigate the methods of calibrating WIM systems to ensure the accuracy of measurements of the weight of vehicles in motion. Factors affecting the accuracy of measurements and methods of their compensation are considered. The results of the study contribute to improving the reliability and accuracy of WIM systems.

The article [9] considers the mathematical modeling of the thermal straightening process of the backbone beam of freight platform cars. The authors investigate the modeling of the thermal straightening process from the perspective of the non-stationarity of various factors.

The article [10] considers mathematical modeling of technological transitions in the production of bent profiles. The results of the study can be used to optimize production technologies.

The conducted literature analysis clearly demonstrates the significant attention of researchers to the problem of determining non-stationary factors of fatigue resistance in freight car joints. Mathematical modeling is a key tool for the quantitative assessment of these factors. Studies emphasize the complexity of predicting the resource of joints due to the variability of operational loads. The influence of non-stationary factors, such as dynamic shocks and vibrations, significantly reduces the service life of elements.

Research methods. To study non-stationary fatigue resistance factors, a mathematical modeling method will be used, which will allow creating a virtual model of a freight car joint and simulating the influence of various operating conditions.

Analysis of the stress-strain state of freight car joint elements under the action of non-stationary loads will be carried out using numerical methods, in particular the finite element method. In order to assess the influence of random load fluctuations on the accumulation of damage in the joint material, probabilistic and statistical methods and the theory of random processes will be used. Experimental studies of the fatigue strength of joint material samples under non-stationary loading conditions will be carried out to verify the results of mathematical modeling.

Object and subject of research. The object of research is the processes of damage accumulation and destruction of joints of load-bearing elements of freight car structures under conditions of non-stationary fatigue resistance factors.

The subject of the study is the regularities of the influence of non-stationary fatigue resistance factors (variable stress amplitudes, load frequencies, average stress levels) on the fatigue strength characteristics and predicted resource of freight car joints, determined on the basis of mathematical modeling and analysis.

Statement of the problem. The increasing intensity of operation of freight cars places increased demands on the reliability of their connections. One of the key problems is the accumulation of fatigue damage under the action of cyclic loads. Traditional methods of calculating the resource are often based on stationary assumptions about fatigue resistance factors. However, in real operating conditions, these factors, such as temperature, humidity and corrosive environment, are non-stationary and can change significantly. This leads to inaccuracies in predicting the residual resource of connections.

The non-stationarity of fatigue resistance factors determines a complex relationship between applied loads and the rate of damage accumulation. Changes in external conditions can both accelerate and slow down the fatigue failure process. Insufficient consideration of this non-stationarity can lead to premature failure of critical structural elements. Therefore, there is an urgent need to develop adequate methods for assessing the impact of non-stationary factors on the fatigue life of freight car joints.

Purpose and objectives of the study. The aim of this work is to develop a mathematical model that takes into account non-stationary fatigue resistance factors for predicting the service life of freight car joints. The study is aimed at quantitatively assessing the impact of variable loads and operating conditions on the accumulation of damage in key structural elements. The results obtained will allow to increase the accuracy of predicting the residual service life and optimize the maintenance strategies of the car fleet.

To achieve the set goal, the following tasks were solved:

- identify and classify the main non-stationary fatigue resistance factors affecting freight car joints during their operation;
- to develop mathematical models that describe the dynamics of changes in non-stationary fatigue resistance factors over time;
- to investigate the impact of each of the identified non-stationary factors on the accumulation of damage in key joints of freight cars;
- to create a mathematical model that comprehensively takes into account the influence of non-stationary fatigue resistance factors on predicting the service life of freight car joints;
- to conduct a numerical analysis of the developed model for different operating modes and parameters of freight cars;
- verify the adequacy of the developed mathematical model by comparing the modeling results with available experimental data or the results of other studies.

Outline of the main material of the study. The linear hypothesis of fatigue damage accumulation, proposed by A. Palmgren (1924) and developed by M. Mayer (1939), is the basis for calculating the durability of materials under cyclic loading. The hypothesis states:

$$\sum_{i=1}^{r}\frac{n_i}{N_i}=1 \quad (1)$$

$$\left(\sigma_{ai}\geq\sigma_{-1\partial}\right)$$

where n_i – number of cycles at voltage σ_i;

N_i – number of cycles to failure under stress σ_i.

For practical calculations, the Baskin equation [11] is used, which relates the durability N with the amplitude of stresses σ:

$$\sigma_a = \sigma_{f'} \cdot (2N)^b, \quad (2)$$

σ_a – stress amplitude (MPa);

$\sigma_{f'}$ – endurance coefficient (MPa);

N – number of cycles to failure;

b is the fatigue strength index (-0.05 to -0.12 for metals).

Alternative form (for SN curve)

$$\sigma^m \cdot N = C, \quad (3)$$

where m – power index (depends on the material, for steels $m \approx 3...8$);
C is the material constant.

For variable load with different amplitudes σ_i Baskin's equation integrates with the Palmgren-Mayer hypothesis:

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = 1 \text{ або } \sum_{i=1}^{k} \frac{n_i \cdot \sigma_i^m}{C} = 1. \quad (4)$$

However, the real process of fatigue damage accumulation is nonlinear, due to the change in fatigue resistance characteristics, primarily the endurance limit, as the design life develops. Baskin equationaccording to the Palmgren-Mayer hypothesis: has a number of disadvantages, such as:

1. Linear damage accumulation – does not take into account the interaction of cycles.
2. Not suitable for low-cycle fatigue (large plastic deformations).
3. Does not take into account environmental influences (corrosion, temperature).

Taking this fact into account is the basis of the kinetic theory of fatigue by E.K. Pochtenny [12]. The kinetic theory of Pochechny provides a more realistic assessment of the resource, especially for critical structures, where traditional methods give non-conservative results. Its implementation requires additional experimental data, but allows to significantly increase the reliability of calculations. The generalization of experimental data of a number of researchers made it possible to establish the following:

– under regular loading, higher voltage has a greater damaging effect, as a result of which the intensity of the decrease in the endurance limit is higher in cases where higher voltage was applied;

– with irregular block loading, depending on the nature of the load alternation, "training" or strengthening effects appear, which reduce or increase the intensity;

– at the moment of failure of the structure, the ultimate value of the endurance limit is different from zero;

– the greatest damaging effect is caused by short-term overloads.

The nonlinearity of fatigue damage accumulation can be described by the Palmgren-Mayer hypothesis taking into account the kinetics of the endurance limit.

Henry's theory addresses the mechanisms of fatigue failure of materials, in particular the role of local plastic deformations in the process of damage accumulation. It complements the classical approaches (Baskin, Palmgren-Mayer) and the kinetic theory of Pochechny, emphasizing the micromechanical aspects of fatigue. The theory uses the plastic strain accumulation criterion [13]:

$$\Delta \epsilon_p \cdot N_f^{\alpha} = C, \quad (5)$$

$\Delta\epsilon_p$ – amplitude of plastic deformation per cycle;
N_f – number of cycles to failure;
α, C are material constants (for steels $\alpha \approx 0.5...0.7$).

For stresses, the formula is similar to the Baskin equation, but taking into account plasticity:

$$\sigma_{Ri} = \sigma \frac{1 - \frac{n_i}{N_i}}{\frac{\sigma}{\sigma_R} - \frac{n_i}{N_i}} \quad (6)$$

Henry's theory fills the gap between macroscopic (Baskin) and microscopic (dislocation) fatigue models.

S.V. Serensens hypothesis is a development of classical approaches to the assessment of fatigue failure of materials, in particular the linear Palmgren-Mayer hypothesis. It takes into account the nonlinear nature of damage accumulation and the influence of additional factors, such as stress concentration, surface quality and residual stresses [14].

$$\frac{\sigma_{Ri}}{\sigma_R} = 1 - \left(\frac{n_i}{N_i}\right)\left(\frac{\sigma}{\sigma_R} - 1\right) \frac{1}{\left(\frac{\sigma}{\sigma_R} - \left(\frac{n_i}{N_i}\right)\right)^2} \quad (7)$$

where σ_{Ri} σ_R – endurance limits of the damaged and original materials, respectively; $\frac{\sigma}{\sigma_R}$ degree of overload; m, mi – characteristics of the slope of the left branch of the primary and secondary fatigue curves.

Hypothesisnonlinear accumulation of fatigue damage Marko – Starkey [15].

One of the first hypotheses of nonlinear damage accumulation was proposed by Marko and Starkey in 1954. It is based on the following propositions.

Damage curves for any amplitude value of symmetrical sinusoidal stresses can be described by the relations:

$$\sum \frac{n}{N} \approx \int_0^1 \frac{1 + \frac{N_1}{N_2} + \frac{N_1}{N_3} + ... + \frac{N_1}{N_i}}{1 + \frac{N_1}{N_2} r_2 D\left(\frac{r_2 - 1}{r_2}\right) + ... + \frac{N_1}{N_i} r_i D\left(\frac{r_i - 1}{r_i}\right)} dD, \quad (8)$$

In the article by E.K. Pochtenny [16], a modified approach to the assessment of fatigue life of materials is proposed, which takes into account the decrease in the endurance limit in the process of damage accumulation. This method is a development of the classical linear Palmgren-Mayer hypothesis, but includes corrections for material degradation under the action of cyclic loads.

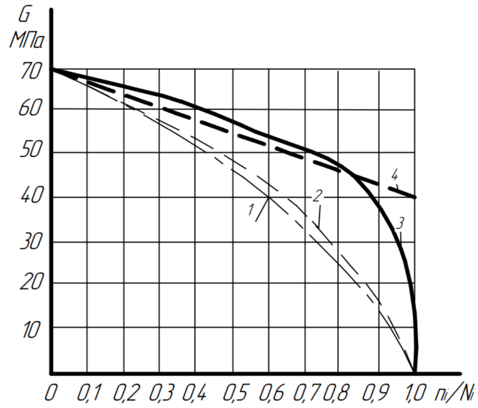
$$\sigma_{Ri} = \sigma_R \left(1 - \frac{n_i}{N_i}\right)^{1/m} \qquad (9)$$

Regardless of the degree of overload, the value of the endurance limit at the moment of failure, calculated by equation (7), is zero, which is not true. Expression (8) in the range of overload degrees greater than two gives underestimated values of the endurance limit for fixed fractions of the developed resource. The parameter mi, which characterizes the accumulated fatigue damage, depends on the history of the load, and therefore the correct use of expression (9) requires substituting instead of it the functional dependence of the characteristic of the slope of the secondary curve on the fraction of the developed resource and the degree of overload, the finding of which in itself is a difficult task. The assumption in expression (10) about the invariance of the parameters NG and m makes it independent of the applied stresses, which is also unacceptable. Thus, none of the considered equations satisfies all the requirements formulated above.

In the adjusted linear hypothesis of B.P. Kogaev, to take into account the change in the endurance limit, it is recommended to adjust its initial value σR to the calculated value R (where K is the coefficient of the lower limit of damaging stresses, which is chosen a priori from the interval of empirical values of K from 0 to 1.0 [17]). The coefficient K depends on the intensity of the decrease in the endurance limit, which is determined for a specific structure by the spectrum of operational loads: the greater the proportion of the load amplitude spectrum is above the endurance limit, the smaller K.

Determining the equation of its reduction by direct experimental method requires a large amount of tests, which led to the hypothetical nature of the criteria proposed to describe the reduction of the endurance limit, the main of which are the criteria presented in (Fig. 1).

In the simplest case, it can be assumed that the abscissa of the fracture point NG and the characteristic of the angle of inclination of the left branch of the fatigue curve m are invariant. In this case, as the damage accumulates, the fatigue curve will fall down vertically, as shown in (Fig. 2).



1 – D. Henry; 2 – CB Sørensen;
3 – E.K. Pochtenny; 4 – Marko – Starkey

Fig. 1. Decrease in endurance limit during accumulation of fatigue damage, described by the criteria

Then, according to equation (1) for 0 < ni / Ni < 1, with ni / Ni = const, we can write:

$$\sigma^m \left(N_i - n_i\right) = \sigma_{Ri}{}^m N_G \qquad (10)$$

Taking into account the assumption of invariance of m and NG, it follows from equation (10) that as the resource increases, the decrease in the endurance limit is described by dependence (9).

$$\sigma_{Ri} = \sigma_R \left(1 - \frac{n_i}{N_i}\right)^{1/m}$$

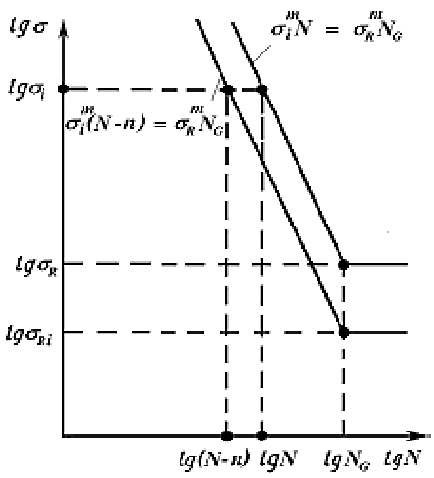


Fig. 2. Decreasing endurance limit as damage accumulates

Thus, under the above assumptions, the change in the endurance limit of the initial material is described by a decreasing function that depends only on the degree of fatigue damage (fraction of the service life), and at the moment of failure it becomes zero. Domestic and foreign researchers have experimentally proven [12–15] that the rate of decrease in the endurance limit of steel structures depends not only on the magnitude of fatigue damage, but also on the degree of overload.

In addition, the mathematical description of the decrease in the endurance limit must be carried out in accordance with the change in the shape of the entire fatigue curve, in particular the angle of inclination of its left branch. In this regard, to describe the endurance limit, it is necessary to make appropriate adjustments to the relationship (10).

Given the large volume of tests required to obtain the dependence of the change in the endurance limit of full-scale structures by direct experimental methods, indirect methods are promising, in the opinion of the authors.

The physical justification of the shape of the curve of change in the endurance limit is based on the similar nature of the change in the damage energy of fracture. Considering that the level of damage energy in the first approximation is an indirect characteristic of the accumulated fatigue damage and is correlated with the endurance limit, it is possible to assess the nature of the change in the latter at different degrees of overload based on the results of measurements of the power supplied to the sample.

For the mathematical interpretation of the decrease in the endurance limit, taking into account the above assumptions, it is proposed to introduce into formula (9) the kinetic coefficient of fatigue damage accumulation, which depends on the relative durability and the degree of overload C, taking into account the correction, the proposed dependence (φ-criterion) has the form:

$$\sigma_{Ri} = \varphi\sigma_R \left(1 - \frac{n_i}{N_i}\right)^{1/m\varphi} \tag{11}$$

$$\varphi = \exp\left(\frac{n_i}{N_i} lg \frac{\sigma}{\sigma_R}\right) \tag{12}$$

The proposed dependence satisfies all the requirements formulated at the beginning of the article. In addition, under irregular loading, characterized by large overload degrees and small resource fractions, a slight (from 0.5 to 1.5%) increase in the endurance limit is satisfactorily described by reducing the alternation of stresses in the program block, which can be interpreted as a manifestation of the "training effect" [16]. The reason for such an effect of large stresses is the uneven distribution of plastic deformation in the weld zone and the formation of residual compressive stresses during unloading, which contribute to the increase in the endurance limit. The obtained dependence makes it possible to take into account the change in the endurance limit in calculations of the fatigue life of load-bearing systems.

The calculation of the cyclic durability of the connection node of the pivot beam with the ridge beam of the gondola frame was made for two selected operating modes: movement on a broken dirt road (mode A) and on a dirt road in satisfactory condition (mode B).

When calculating the resource of the supporting system of the gondola frame of the highest accuracy (σ = 7%) achieved using φ-criterion. In this case, the error is not directed to the durability reserve. In general, it should be noted that the use of predictive methods for calculating the durability of load-bearing systems, based on the use of criteria that take into account the regularities of reducing the endurance limit during operation, allows you to achieve high accuracy of the calculation. In our case, the fluctuations of the total relative error of the calculated estimate are within 7% ≤ σ ≤ 27%. This confirms the effectiveness of the methods of the kinetic theory of fatigue, which is based on taking into account real physical processes of fatigue damage accumulation.

The presented computational and experimental data on the assessment of durability allow us to make an attempt to modify the method of calculating durability, based on the application of the linear hypothesis. The essence of the modification is to replace the real fatigue curve, obtained from the results of tests during regular loading, with some fictitious one, which takes into account the change in fatigue resistance factors as the resource is developed (Fig. 3).

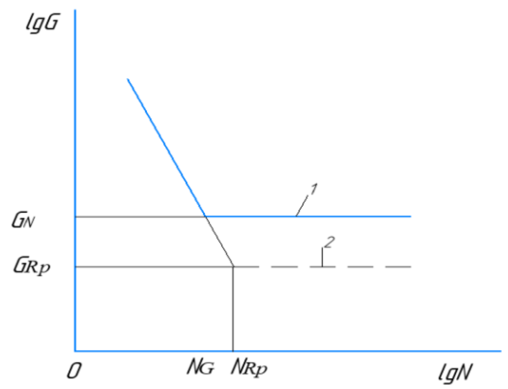


Fig. 3. Before determining the design fatigue curve

Real fatigue curve 1 with parameters σ_R, NG, m is replaced by the calculated curve 2 with parameters σ_R, NGp, m.

Calculating quantities σ_{Rp}, NGp is performed according to the formula:

$$\sigma_{Rp} = K\sigma_R \quad (13)$$

$$lgN_{Gp} = lgN_G + mlg\left(\frac{\sigma_R}{\sigma_{Rp}}\right) \quad (14)$$

For some generalized curve of the decrease in the endurance limit (Fig. 4), the weighted average value of the endurance limit.

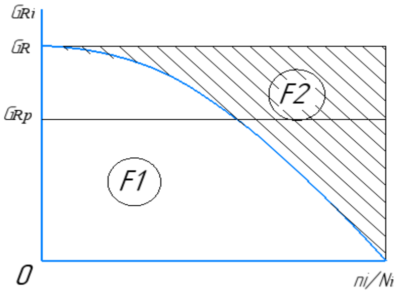


Fig. 4. Before determining the lower limit of damaging stresses

The results obtained show that the lowest accuracy is characteristic of methods based on the formulas:

$$\sigma_{Rp} = \int_0^1 \sigma_{Ri}\left(\frac{n_i}{N_i}\right) d\left(\frac{n_i}{N_i}\right) \quad (15)$$

from where we determine K according to the criteria of D. Henry, CB Sørensen and E.K. Pochtenny, taking into account that the integral in expression (15) is taken in explicit form:

– for D. Henrys criterion

$$K = \frac{\int_0^1 \sigma \frac{\left(1-\frac{n_i}{N_i}\right)}{\left(\frac{\sigma}{\sigma_R}-\frac{n_i}{N_i}\right)} d\left(\frac{n_i}{N_i}\right)}{\sigma_R} = \frac{\sigma\left(\frac{\sigma}{\sigma_R}-1\right) ln\left[\frac{\frac{\sigma}{\sigma_R}}{\frac{\sigma}{\sigma_R}-1}\right]}{\sigma_R} \quad (16)$$

– for the criterion S.V. Serensen

$$K = 1 - \int_0^1 \left(\frac{n_i}{N_i}\right)\left(\frac{\sigma}{\sigma_R}-1\right)\frac{1}{\left(\frac{\sigma}{\sigma_R}-\left(\frac{n_i}{N_i}\right)\right)^2} d\left(\frac{n_i}{N_i}\right) =$$

$$= 1 + \frac{\frac{\sigma}{\sigma_R}-1}{2} ln\left[\frac{1-\frac{\sigma}{\sigma_R}}{\frac{\sigma}{\sigma_R}}\right] \quad (17)$$

– for the criterion E.K. Pochtenny

$$K = \int_0^1 \left(1-\frac{n_i}{N_i}\right)^{1/m} * d\left(\frac{n_i}{N_i}\right) = \frac{m}{m+1} \quad (18)$$

Substituting the numerical values of the parameters into the obtained expressions, we obtain the value of K. The calculation results are summarized in Table 1. With sufficient accuracy, we can assume K = 0.6...0.75.

The durability of the nodes has been calculated. of freight car joints using the linear hypothesis and calculated fatigue curves. The calculation results are summarized in Table 2.

Table 1

Results of calculating the coefficient K

Name criterion	Regime	
	A	B
D. Henry	0.598	0.645
CB Serens	0.634	0.691
E.K. Pochtenny	0.757	0.757

Table 2

Results of calculating the durability of welded joints of car frames based on a modification of the linear hypothesis

No.	K	Regime	Ni,cycles	Li, km	L, km*
1	0.6	A	453258	165250	865820
		B	789520	1662510	-37.2
2	0.7	A	568952	212520	1202120
		B	1319805	1952140	-5.65

The denominator contains the calculation error (%) relative to the operational durability, the minus sign indicates that the error is directed towards the durability margin.

Conclusions. The primary analysis of the results given in the tables shows that the durability calculated by the linear hypothesis exceeds that calculated by the adjusted linear hypothesis by more than 5 times and the durability calculated using the criteria for reducing the endurance limit by 1.37 to 1.7 times. The results obtained show that the lowest accuracy is characteristic of methods based on the direct application of the linear damage summation hypothesis and the adjusted linear hypothesis.

Note that for K = 0.7 the calculated endurance limit σ_{Rp} = 48.4 MPa. Calculated abscissas of the fracture points of the fatigue curve $_{NGp}$ = 3.7*106 cycles. Thus, for the considered design variants of the nodes, the application of a modified linear hypothesis using calculated fatigue curves can provide high accuracy of predictive calculation of durability at the value of K = 0.7. In addition, a positive property of the proposed method is the direction of the error in the durability margin.

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Фомін О.В., Бурлуцький О.В., Кубрак А.В., Голуб Г.М., Фурсина А.Д. НЕСТАЦІОНАРНІ ФАКТОРИ ОПОРУ ВТОМИ ТА ЇХ ВПЛИВ НА РЕСУРС З'ЄДНАНЬ ВАНТАЖНИХ ВАГОНІВ: МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ ТА АНАЛІЗ

Стаття присвячена математичному моделюванню та аналізу запропоновано модифікований варіанту лінійної гіпотези накопичення втомних ушкоджень, ця модифікація класичної лінійної гіпотези (Пальмгрена-Майера) дозволяє точніше прогнозувати залишковий ресурс конструкції. за якого використовується умовне значення межі витривалості, що визначається коефіцієнтом нижньої межі пошкоджуючих напружень.

Лінійна гіпотеза накопичення усталостних пошкоджень, запропонована А. Пальмгреном (1924) та розвинена М. Майером (1939), є основою для розрахунку довговічності матеріалів при циклічному навантаженні. На основі аналізу непрямої характеристики накопиченого втомного пошкодження – енергії руйнування локальних моделей вузлів рам вантажних вагонів визначено залежність зниження *межі витривалості від частки виробленого ресурсу, який враховує динамічне зниження межі витривалості у процесі експлуатації. До найбільш значних недоліків лінійної теорії відноситься те, що вона не описує впливу черговості напружень різних рівнів.*

Таким чином, для розглянутих конструктивних варіантів вузлів несучих вузлів вантажних вагонів, застосування модифікованої лінійної гіпотези з використанням розрахункових кривих втоми може забезпечити високу точність прогнозуючого розрахунку довговічності при значенні К = 0,735. Крім того, позитивною властивістю пропонованого методу є спрямованість похибки в запас довговічності.

Наведено розрахункове обґрунтування нижньої межі пошкоджуваної напруги. Запропонована модифікація лінійної гіпотези. Враховує нелінійність через зниження σ_{-1}. та введення σ_{min}. Підтверджена енергетичними та експериментальними даними. Зменшує ризик переоцінки ресурсу на 30–50% порівняно з класичним підходом.

Ключові слова: *залізничний транспорт, рухомий склад, вагон, машинобудівні конструкцій, довговічність, комп'ютерні технології, автоматизація, комп'ютерне моделювання.*