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РУХОМИЙ СКЛАД ЗАЛІЗНИЦЬ І ТЯГА ПОЇЗДІВ

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OPERATION CHARACTERISTICS OF ELECTRIC TRAINS ER1, ER2 BEYOND DESIGNED SERVICE LIFE

Purpose. The aim is to develop the scientific substantiation technical regulation of measures and conditions in electric trains, series ER1, ER2 beyond the extended period of operation life (over 50 years). **Methodology.** To achieve this goal the scientific publications analysis on the survivability of the basic elements of supporting constructions that are loaded with dynamic alternating loads was carried out. The results analysis of vibration bench tests of bogie frames of electric trains ER1, ER2, which were obtained by using the developed technique for such tests with authors, was carried out too. Technical solutions with appropriate measures under which it is possible to extend the operation life of bearing structures of electric trains ER1 and ER2 were developed over 50 years. **Findings**. Results were obtained on the complex basis of conducted experimental and theoretical research. They have promoted to the working out the methodology for assessing the period of crack development in the tensest points of main bearing structures of bogie frames and bodies of electric trains ER1, ER2 with achieving their dangerous sizes. This allowed developing a technical regulation measures to ensure the safe operation of the main bearing structures of bogie frames and bodies of electric trains ER1, ER2 beyond 50 years. **Originality**. To ensure the safe trains operation, series ER1, ER2 the method estimation of crack development term in the tensest points of bearing structures of bogie frames and bodies with achieving their dangerous sizes was worked out. **Practical value.** The technical regulation of measures ensuring the safe operation of the main bearing structures of bogie frames and bodies of electric trains ER1, ER2 beyond 50 years was developed.

Keywords: bogies; body; computational models; experimental studies; theoretical calculations; electric trains ER1; ER2; stability factor

Introduction

As of the current day the specified operation life of the electric trains, series ER1 and ER2 is extended up to 50 year [5, 7–8]. In order to identify safe operation opportunities of the bearing structures (BS) of individual elements of bogie frames and electric trains bodies, series ER1 and ER2 with operation term more than 50 years the analysis of damage causes of bearing structures of rolling stock, which are operated on the railways of Ukraine exceeding the required service time [2, 5, 7–8] was conducted. The main causes of damage are as follows:

1. The presence of extraneous impurities in to the base metal of a structure or weld joint, improper performance of weld joints;
2. Unsuccessful design of the bearing structures of the rolling stock;

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3. Destruction initiation on the point of effort or BS strength renovation;

4. Incorrect technological intervention in the design of rolling stock;

5. Effect of aggressive environment and seasonal changes in temperature on the bearing structures of rolling stock.

Purpose

The aim is the scientific substantiation development of the technical regulation relatively to conditions and measures during the operation of electric trains, series ER1, ER2 beyond the continuous operation life.

Methodology

To achieve this goal – the scientific substantiation of technical regulations development concerning measures during the operation of electric trains, series ER1, ER2 beyond the continuous operation life (over 50 years) the following actions have been conducted: the scientific publications analysis on the survivability matter of the main elements of bearing structures, which are loaded with dynamic alternating loads [6, 9-14]; The results analysis of the bench vibration tests of bogies frame of electric trains ER1, ER2 was carried out [8]; they had been obtained on the basis of the developed procedure of such tests involving authors' studies and their appropriate scientific support; technical solutions with appropriate measures when it is possible to extend the operation life of the bearing structures of electric trains EF1 and ER2 over 50 years were developed.

Thus, in order to ensure the safe operation of electric trains, series ER2 and ER1 over 50 years it is necessary to develop a calculation method for such operation term, during which in the tensest points of bearing structures of bogies frames and bodies frames the cracks initiation is possible and development with achieving their dangerous sizes. In accordance with date based calculations this technique let the opportunity establish the inspection frequency of bearing structures state of bogies frames and bodies of pointed units of rolling stock and take early actions which will encourage their safe operation.

Findings

The general patterns of crack growth in the bogies frames destruction of electric trains ER1 and ER2. From the safety movement viewpoint of motor car units of rolling stock (MCRS) the issues related to parameters determination of elements survivability of bearing structures their bogie frames and cars that have long-term operation are of current importance [1–4]. At present, a great number of publications on the issues related to survivability analysis of different designs elements [11–14].

In this paper the results of the fulfilled comprehensive research are presented. In it the stress-strain state in the most loaded elements of bearing structures of MCRS bogie frames during the crack initiation phase, their development in the actual designs is analyzed. They were observed during the vibration bench tests perfomance [5, 7–8].

Discussing bearing structures behavior under variable load impact one cannot raise the problems concerning macroscopic cracks behavior since their appearance when structure has lost its bearing capacity.

The origin of cracks in metals has a physical basis, which is related to its behavior on submicroscopic level of material structure, where all metals have monocrystalline structure, but with some imperfection in the form of vacancies and dislocations.

In the mechanical stress area dislocations can interact and move around. The most probable movement is shift or slip of crystalline layers relative to each other, the greatest sensitivity to load is at angle of 45° to the direction of the load action. During this process, the dislocation lines are bound to move to the crystal surface, where they can be seen as microscopic strips, namely slip strips, on which grooves act as microcracks nucleation centers that propagate along the intergranular boundaries. These cracks are most sensitive to the stress components directed at an angle of 90° to the cracks surface. They will grow spasmodicly under the cyclic load effect.

Let us consider a small flat crack that goes from the surface. Local stress distribution can be described in a local coordinate system where x-and z- axis are perpendicular to the crack front line, as shown in the Fig. 1.

Expressing the linear equation of strains and stresses link in polar coordinates (r, θ) and assuming that these variables are independent, local stress components can be written as

$$\sigma_{ij} = R(r)\Theta_{ij}(\theta) \qquad (1)$$

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On the surfaces, the position of which is determined $\theta = \pm\pi$ relatively to the crack growth direction both the normal stresses and tangential one are zero.

The parameter describing stress which explains this requirement should have a radial view function

$$R(r) = r^{\frac{n}{2}-1}, \qquad (2)$$

where n – is zero value or the whole number. Real value will be $n = 1$, which gives a singularity in the crack front with order -1/2.

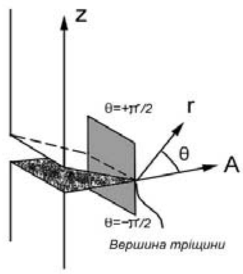

Fig. 1. The coordinates describing the dependence between the local deformations and stresses in the crack tip front

For this value the stress components can be written as

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}}\Theta_{ij}(\theta) \qquad (3)$$

here $\sqrt{2\pi}$ – is normalizing factor, introduced for convenience. Coefficient K, common to all stress components, means intensity of stress. It depends on crack shape and tensor orientation of nominal stress and proportional to the prevailing component and nominal stress, that is determined as σ_∞.

In some special cases, the stress intensity K can be derived analytically using integration of complex function. For a long flat crack in metal sheet, length $2x$, perpendicular to longitudinal tension, components of local stress are

$$\sigma_{ij} = \sqrt{\frac{\chi}{2r}}\sigma_\infty\Theta_{ij}(\theta);\ K = \sqrt{\pi\chi}\sigma_\infty. \qquad (4)$$

Then, even if nominal stress σ_∞ are small, local stress components σ_{ij} in crack front at $r = 0$ can be extremely high. Theoretically, they can be much higher than tensile material strength.

This heterogeneity in the field of stress can lead to material destruction in a very small region near the crack tip and thus increase this crack. However, if stress is small, this heterogeneity will be nullified when the crack front increases to a distance comparable to the size of a grain.

The basic assumption of destruction mechanics is that crack growth is associated with changes in stress intensity K. Stress cycle determines the maximum K_{max} and minimum stress intensity K_{min}, with the stress intensity range

$$\Delta K = K_{\max} - K_{\min}$$

One cycle increases crack depth x on small quantity Δx:

$$\Delta x = \begin{cases} C(\Delta K)^m \uparrow \Delta K > \Delta K_0 \\ 0 \qquad\quad \uparrow \Delta K \le \Delta K_0 \end{cases}. \qquad (5)$$

This expression is known as the law of cracks development Paris-Erdogan. Here C, m and K_0 – are empirical constants, obtained from laboratory tests. If one will build view of graphical dependency according to correlation (5), we will receive diagram type corresponding to Wohler's diagram, in a famous Palmhrena-Meiner method. Curve or diagram da/dN can be called the curve, which shows an increase of crack length per cycle as a. The crack length a serves to describe semi-elliptical cracks, where a and b mean long and short semiaxis. a – describes the depth of cracks, a $2b$ – is crack opening.

Since the curve of crack growth is connected only with the characteristics of the material, and not with specific geometric features, the sample may be small, but load frequency is high, often in the audio frequency range. While conducting measurements on one sample, one can obtain some points of curve da/dN in a short time. Wohler diagram, on the contrary, is connected both with the material and the detail form, so in order to get just one point on this curve, it is necessary to test one sample before destruction. Consequently, the analysis of crack growth for solving the problem is more acceptable than the classic fatigue tests.

Calculated ratio for crack resistance evaluation of bogie frames electric trains ER1, ER2. During test bench vibration of bogie frames of electric trains ER1 and ER2, they were brought to the loss of bearing capacity [7–8]. Thus, the test results

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provide information both on their designs endurance and resistance to their destruction.

Depending on the location of the strain gage, in the process of crack growth, stress may increase (Fig. 2), when the gage is on the way of crack growth, it decreases (Fig. 2, *b*); when the crack passes it by and unloads a part of construction, or it can remain insensitive to crack growth (Fig. 2, *c*). In any case, the value change in stress at the same excitation force may indicate about presence of cracks that is growing.

At the same excitation force crack growth time may be evaluated as follows

$$\tau_{з\min} = \min\left(\frac{N_{зi}}{N_c} T_c\right) \qquad (6)$$

where $\tau_з$ – crack growth time; $N_{зi}$ – is load cycles quantity when level change of i gage of strain occurs; N_c – is total quantity of load cycles before bearing capacity losses by the bogie frame no. T_c – is calculated time of operation at N_c load cycles of structure.

a *b* *c*

Fig. 2. Possible stress behavior in the elements of structure in the tests process at different location of strain gage relatively to the crack

For the bogie frames, in accordance with the above mentioned, time evaluation of the structure destruction was carried out. It was foreseen that in each case of the test they had stopped under abrupt change of structure reaction on stress. It means losing the bearing capacity by it. Calculations results (in normal climatic environment) are presented in the Table 1.

Besides one should consider two factors that effect on crack growth rate:

– Asymmetry of stress cycle;

– Environment temperature.

Table 1

Evaluation of the resistance period to the destruction of the bogie frames of electric trains ER12, ER2

№	№ bogie frames	$N_{зi}$	N_c	T_c, years in	$\tau_з$, years
1	2	3	4	5	6
1	385	51 034	524 309	15	1.46
2	427	198 450	1 393 951	15	2.14
3	40	–	1 004 400	15	–
4	170	180 000	580 000	15	4,66
5	397	251 200	1 455 440	15	2.59

During test performance stress has been supported similar to operating regime of the structure under standard load.

Concerning the environment temperature, results of previous research have showed, that in the cold period of a year crack growth rate decreases approximately on 60%. At the same time, critical crack length in the winter period decreases practically in four times. That is why in the winter period (at -30°C) the crack may develop up to critical level approximately in 4-5 months.

Thus, the conducted estimation to destruction resistance of bogie frames of electric trains, series ER1 and ER2 allows making the following conclusions:

1. Hypothetically, in the winter period crack can develop up to a critical level approximately in 4-4.5 months.

2. Inspection of bearing structures state of bogie frames is reasonable to perform two times per year: the first is auxiliary – during the month from the second part of October; the other, primary, – during the month, from the second part of March.

3. To keep inspection schedule both for bodies of electric trains and bogie frames.

Originality and practical value

To ensure the safe operation of electric trains, series ER1, ER2 the method to assess the term of the cracks development in the most intence points in bearing structures of bogie frames and bodies with achieving their dangerous sizes and technical regulation measures to ensure the safe operation exceeding 50 years was developed.

Technical regulation and technical decisions development upon operation time continuous of

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main bearing structures of electric trains, series ER1, ER2. For ensuring safety operation of pointed items of rolling stock by railway men in motor car depot the proper measures had to be taken during repair. Content of these measures, on the base of above mentioned results and conclusions, was summarized in the form of developed technical regulation concerning bearing structures operation of electric trains, series ER1, ER2.

This regulation is based on the following positions:

1. Electric trains ER1, ER2 operation during the period after expiration of their operation terms (that are scientifically grounded and specified) is continued individually for every car of the electric train on their factual state.

2. Works regulation concerning support of efficient state of electric trains bearing structures (bogie frames, body frames) is created on the base of step-by-step prolongation methods of their service term.

3. Frequency, seasonal prevalence and inspection volumes are determined on the base of bench vibration tests results of bogie frames of electric trains ER1, ER2.

Frequency determination, seasonal prevalence and inspection volumes of load-bearing structures of electric trains ER1, ER2. For features comparison of crack development support we will take conditionally, that crack in the winter period develops quicker in four times, in spring and autumn period and when the temperature -30° is kept during three winter months.

Also, at monthly mean temperatures decrease below -30°, works regulation on individual extension of cars service term of electric trains has to be correct.

Information to calculate the proper inspection frequency of bearing structures of electric trains ER1, ER2 is presented in the Table 2.

So, conditional quantity of months before destruction during tests in normal climatic environment two times less.

At the same time, the average period from destruction to bearing capacity loss by the structure may be 8.8 months. This is coordinated badly between routine repair maintenance.

Taking into account above mentioned material, one should suppose rational realization of annual inspection in accordance with the schedule 1½, namely [8], before the winter period one should realize diagnostics of bearing structures accordingly to the schedule of step-by-step extension of the service term upon the regulation PR3, and in spring – inspection upon the regulation PR2.

Table 2

Information to calculate the inspection frequency of bearing structures of electric trains ER1, ER2

№	Conditional № month	Conditional crack growth rate	Note
1	2	3	4
	1	4	Winter
	2	4	Winter
	3	4	Winter
	4	1	
	5	1	
	6	1	
	7	1	
	8	1	
	9	1	
	10	1	
	11	1	
	12	1	
	13	4	Winter
	14	4	Winter
	15	4	Winter
	16	1	
	17	1	
	18	1	
	Average rate	2	

Reparability issue of bearing structures of bogie frames and electric train's bodies, renovation of their toughness is a separate scientific issue. It is not highlighted in this paper.

Inspection frequency of bogie frames of electric trains ER1, ER2 was analyzed. It let make the following conclusions:

1. The average period from the crack occurrence to bearing capacity loss by the structure may form 8.8 months.

2. Above pointed index of bearing structures survivability of electric trains coordinate badly with routine repair maintenance.

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3. One should suppose rational realization of an annual inspection accordingly to the schedule ½, namely, before the winter period one should realize diagnostics accordingly to the schedule of step-by-step extension of the service term upon the regulation PR3, and in spring – inspection upon the regulations PR2.

4. Reparability issue of bearing structures of bogie frames and electric train's bodies, renovation of their toughness is a separate scientific issue. It is not highlighted in this paper.

Conclusions

1. Destruction causes analysis of rolling-stock bearing structures let make the conclusions. The main destruction causes are as follows:

– The presence of extraneous impurities in to the base metal of a structure or weld joint, improper performance of weld joints;

– Unsuccessful design of the bearing structures of the rolling stock;

– Destruction initiation on the point of effort or BS strength renovation;

– Incorrect technological intervention in the design of rolling stock;

– Effect of aggressive environment and seasonal changes in temperature on the bearing structures of the rolling stock.

2. Analysis of the vibration bench tests of bogie frames of electric trains ER1 and ER2 are as follows:

– The stress level on the destruction stage of the bogie may vary.

– These changes are fixed in most parts of the studied frames.

– As a standard piece for resistance evaluation to destruction it can be taken the bogie frame of a motor car of electric trains ER1, no. 397.

– Taking into account that tests were conducted under normal climatic environment, changes in the characteristics of crack resistance should be considered separately.

3. Conducted resistance evaluation to destruction of bogie frames for electric trains ER1 and ER2 let make the following conclusions:

– Hypothetically, in the winter period crack can develop up to a critical level approximately in 4-4.5 months.

– Inspection of bearing structures state of bogie frames is reasonable to perform two times per year: the first is auxiliary – during the month from the second part of October; the other, primary, – during the month, from the second part of March.

– To keep inspection schedule both for bodies of electric trains and bogie frames.

4. The conducted frequency evaluation of bogie frames of electric trains ER1-ER2 allows making the following conclusions:

– Average period from destruction to the loss bearing capacity by the structure may be 8.8 months.

– Above pointed survivability index of bearing structures for electric trains coordinate badly between routine repair maintenance.

– One should suppose rational realization of the annual inspection accordingly to the schedule ½, namely, before the winter period one should realize diagnostics accordingly to the schedule of step-by-step extension of the service term upon the regulation PR3, and in spring – inspection upon the regulations PR2.

– Reparability issue of bearing structures of bogie frames and electric train's bodies, renovation of their toughness is a separate scientific issue. It is not highlighted in this paper.

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ОСОБЛИВОСТІ ЕКСПЛУАТАЦІЇ ЕЛЕКТРОПОЇЗДІВ ЕР1, ЕР2 ЗА МЕЖАМИ ПРИЗНАЧЕНОГО СТРОКУ СЛУЖБИ

Мета. У роботі необхідно провести наукове обґрунтування розробки технічного регламенту заходів та умов експлуатації електропоїздів серій ЕР1, ЕР2 за межами подовженого терміну експлуатації (понад 50 років). **Методика.** Для досягнення поставленої мети було проведено аналіз наукових публікацій з питань живучості основних елементів несучих конструкцій, які навантажуються динамічними знакозмінними навантаженнями. Також проведено аналіз результатів стендових вібраційних випробувань рам візків електропоїздів ЕР1, ЕР2, які були отримані на підставі розробленої методики проведення таких випробувань за участю авторів роботи та виконано відповідне наукове супроводження. Розроблені технічні рішення з відповідними заходами, при виконанні яких стає можливим продовжити строк експлуатації несучих конструкцій електропоїздів ЕР1 і ЕР2 понад 50 років. **Результати.** На підставі комплексу проведених експериментальних та чисельних теоретичних досліджень отримано результати, які сприяли розробці методики щодо оцінки терміну розвитку тріщин в найбільш напружених точках основних несучих конструкцій рам візків та кузовів електропоїздів ЕР1, ЕР2 з досягненням їх небезпечних розмірів. Це надало можливість розробити технічний регламент заходів, що забезпечують безпечну експлуатацію основних несучих конструкцій рам візків та кузовів електропоїздів ЕР1, ЕР2 за межами 50 років. **Наукова новизна.** Для забезпечення безпечної експлуатації електропоїздів серій ЕР1, ЕР2 розроблено методику щодо оцінки терміну розвитку тріщин в найбільш напружених точках несучих конструкцій рам візків та кузовів з досягненням їх небезпечних розмірів. **Практична значимість.** Розроблено технічний регламент заходів, що забезпечують безпечну експлуатацію основних несучих конструкцій рам візків та кузовів електропоїздів ЕР1, ЕР2 за межами 50 років.

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ОСОБЕННОСТИ ЭКСПЛУАТАЦИИ ЭЛЕКТРОПОЕЗДОВ ЕР1, ЕР2 ЗА ПРЕДЕЛАМИ НАЗНАЧЕННОГО СРОКА СЛУЖБЫ

Цель. В работе необходимо провести научное обоснование разработки технического регламента мероприятий и условий эксплуатации электропоездов серий ЭР1, ЭР2 за пределами продленного срока эксплуатации (более 50 лет). **Методика.** Для достижения поставленной цели был проведен анализ научных публикаций по вопросам живучести основных элементов несущих конструкций, которые нагружаются динамическими знакопеременными нагрузками. Также проведен анализ результатов стендовых вибрационных испытаний рам тележек электропоездов ЭР1, ЭР2, которые были получены на основании разработанной методики проведения таких испытаний с участием авторов работы и обеспечено соответствующее их научное сопровождени. Разработаны технические решения с соответствующими мерами, при выполнении которых становится возможным продлить срок эксплуатации несущих конструкций электропоездов ЭР1 и ЭР2 более 50 лет. **Результаты.** На основании комплекса проведенных экспериментальных и многочисленных теоретических исследований получены результаты, которые способствовали разработке методики оценки срока развития трещин в наиболее напряженных точках основных несущих конструкций рам тележек и кузовов электропоездов ЭР1, ЭР2 с достижением их опасных размеров. Это позволило разработать технический регламент мероприятий, обеспечивающих безопасную эксплуатацию основных несущих конструкций рам тележек и кузовов электропоездов ЭР1, ЭР2 за пределами 50 лет. **Научная новизна.** Для обеспечения безопасной эксплуатации электропоездов серий ЭР1, ЭР2 разработана методика оценки срока развития трещин в наиболее напряженных точках несущих конструкций рам тележек и кузовов с достижением их опасных размеров. **Практическая значимость.** Разработан технический регламент мероприятий, обеспечивающих безопасную эксплуатации основных несущих конструкций рам тележек и кузовов электропоездов ЭР1, ЭР2 за пределами 50 лет.

Ключевые слова: тележки; кузов; расчетные модели; экспериментальные исследования; теоретические расчеты; электропоезда ЭР1, ЭР2; показатели прочности

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