Assessment of Locomotive and Multi-unit Fatigue Strength Considering the Results of Certification Tests in Ukraine and EU Countries

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Summary

The comparative analysis of methods for assessing the fatigue strength of the rail vehicle used in the Ukraine and the EU is described in this article. As a result of the comparison, the following main differences of the indicated methods are distinguished:
1. In Ukraine, fatigue strength assessment is carried out using the fatigue strength factor, which should not exceed the normative value. In the countries of the European Union, the fatigue strength is evaluated according to the permissible stresses, and the permissible stresses are determined using stress strain diagrams.
2. According to the requirements of the Norms in Ukraine for determining the fatigue strength factor, the endurance limits of standard samples in a symmetrical loading cycle are used. The stress limit diagrams, which are used in European norms, are constructed for characteristic structural elements taking into account the asymmetry of the stress cycle coefficients.
Analytic studies and analysis of experimental data carried out by the author have made it possible to develop a number of recommendations aimed at increasing the reliability of the results of estimating the fatigue strength of load-bearing structures of self-propelled rolling stock and to make proposals for harmonizing the relevant regulatory documents in Ukraine and the EU countries.

Keywords: locomotive, multi-unit, certification, fatigue strength, assessment criteria

1. Introduction

Railway transport is one of the most important branches of economy of many countries in the world, and its successful operation largely depends on the condition of used rail vehicle. Current and unscheduled repairs of rail vehicle lead to significant additional material costs, and the defects of its load-bearing structures, in addition, significantly affect the safety of traffic, as they can lead to emergencies.

In the process of operation, the rail vehicle is subject to time-varying loads. As a result of this action, stresses appear in the load-bearing elements of its structure, which are random functions of time. If the level of these stresses exceeds a certain value, then there occurs the process of gradual accumulation of damages in the material of the part, leading to destruction. This process is called fatigue of the material, and the corresponding destruction – fatigue failure.

Fatigue failure of load-bearing structures of rail vehicle during operation, as a rule, leads to catastrophic consequences, therefore the problem of preventing this phenomenon in railway transport is very actual and can be solved at the stage of certification tests.

2. Research problem and methodology

At the design stage or in the process of admission to operation, at carrying out certification tests for assessing the fatigue strength of the multi-units in Ukraine Railways and abroad, there is used the regulatory framework, based on fundamental researches in the field of material fatigue.

At the same time, it should be noted that the methods of assessing the strength of load-bearing structures of rail vehicle have greatly developed, especially over the past 30 years. There are three main directions:
1) improvement of methods of strength calculating,
2) improvement of methods of experimental research conducting and processing of the obtained information,
3) improvement of the regulatory framework.

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For the computational support of design and simulation of rail vehicle, at the stage of preparation for strength tests, the finite element method (FEM) has become most widely used. The application of the FEM, at the early stages of its development, to the calculation of real structures was fraught with great difficulties. First of all, this was due to the need to prepare a large number of initial data, the complexity of analyzing the results obtained in the course of computational research and the low power of computers that existed at that time. Therefore, with the growth of computer performance, the development of software complexes implementing the FEM went along the path of creating an intuitive interface, with the ability to visualize both the raw data and the results of the calculation. Modern software complexes allow creating calculation schemes that practically accurately reflect both the geometry of the structure and the conditions of its loading [11, 13, 14].

The development of methods for carrying out experimental research is mainly associated with the use of increasingly sophisticated hardware that allows digitization and recording of measurement processes directly in a computer. That, in turn, gave impetus to the development of software packages that allow for the almost instantaneous processing of experimental data in accordance with the requirements of regulatory documents [2, 7, 10, 12].

The regulatory framework, on the way to the development of methods for assessing the strength of load-bearing structures of traction rail vehicle, in Ukraine was the most conservative element. This is indicated, in particular, by the data given in the Table 1.

The analysis of data, given in Table 1, allows us to draw two main conclusions:

1. The regulations for assessing the strength of traction rail vehicle operating in Ukraine [6, 16], require urgent updating, as nomenclature of traction rail vehicle and its technical characteristics have changed significantly over the last 30 years.
2. When developing new Regulations, it is necessary to take into account the need for their harmonization with the Regulations applied in other 1520 mm gauge countries (Latvia, Lithuania, Estonia, Russia, Belarus, etc.) and the EU countries. This becomes especially relevant in connection with conclusion of international contracts for supply of new equipment by Ukrainian Railways.

As already noted, the requirements for fatigue strength of the structural components of rail vehicle in all regulatory documents are based on fundamental research. However, the criteria for making this assessment are qualitatively different. In particular:

1. In 1520 mm gauge countries, the assessment of fatigue strength is performed with the application of the fatigue safety factor that shall not exceed regulatory value (for main load-bearing elements of body and bogie frames, according to the Regulations requirements for both locomotives [6] and Regulations for multi-units [16] there is applied equal to two). In European Union countries the fatigue strength assessment is performed according to the acceptable stresses, and the acceptable stresses are determined with application of limit stresses diagrams.

Table 1

Regulatory documents, applicable in Ukraine, Russia and European Union

Ukraine	Other 1520 mm gauge countries	European Union
1. Technical requirements for the design and manufacture of welded structures of locomotive bogies – 1970. 2. Technical requirements for the design and manufacture of welded frames of locomotives – 1972. 3. DSTU 4493-2005. Passenger mainline cars of diesel and electric trains. Safety requirements. 4*. Regulations on calculation and assessment of the strength of load-bearing elements and the dynamic qualities of locomotives – 1998. 5*. Regulations on calculation and assessment of the strength of load-bearing elements and the dynamic qualities of multi-units – 1997.	1. Regulations on calculation and assessment of the strength of load-bearing elements and the dynamic qualities of locomotives – 1998. 2. Regulations on calculation and assessment of the strength of load-bearing elements and the dynamic qualities of multi-units – 1997. 3. GOST R 53077-2008 (bogie, modified with reference to EN 13749-2005). 4. GOST R 53076-2008 (bogie, modified with reference to EN 12663-2000). 5. 5. GOST 33796-2016. Interstate standard. Multi- units. Requirements for strength and dynamic qualities.	1. EN 13749-2011, UIC 615-4 (bogie). 2. EN 12663-2010, UIC 566 (body). 3. ERRI B12/RP17-1997 (limit stress diagrams for various steel grades). 4. DVS 1612:2014-08 (limit stress diagrams for welded steel structures). 5. 5. DVS 1608:2011-08 (limit stress diagrams for welded aluminum and alloys structures).

Note: * – regulatory documents that are not put into effect in Ukraine, but are applied in case of relevant reference in technical task for products.

2. For determination of fatigue safety factor there are applied the endurance limits of references at symmetric loading cycle. Limit stress diagrams, used in European regulations [1, 4, 5, 8, 9, 15], are constructed for characteristic structural elements taking into account the asymmetry coefficients of the stress cycle.

In this connection, it became necessary to compare the results of assessment of the fatigue strength of load-bearing structures of rail vehicle using the above criteria.

According to the Regulations [6, 16] applied in Ukraine, the fatigue strength of load-bearing traction rail vehicle structures is assessed using a fatigue safety factor that should not exceed the normative value. The fatigue safety factor n is determined with the help of the equation:

$$n = \frac{\sigma_{-1}}{\left(k\sigma_v + \psi\sigma_m\right)}, \tag{1}$$

where:

- σ_{-1} – endurance limit of reference at symmetrical loading cycle,
- σ_m – average cycle stress,
- σ_v – amplitude of dynamic stresses,
- ψ – coefficient that takes into account the sensitivity of the metal to the asymmetry of the cycle (at $\sigma_m > 0$, $\psi = 0.3$, at $\sigma_m < 0$, $\psi = 0$); k – effective coefficient, taking into account the decrease in the endurance of the part in relation to the endurance limit of the reference.

The coefficient k is determined from relation:

$$k = \beta_k k_1 k_2 / \gamma \cdot m, \tag{2}$$

where:

- β_k – effective stress concentration factor,
- k_1 – coefficient taking into account the heterogeneity of the part material,
- k_2 – coefficient taking into account the influence of internal stresses in the part,
- γ – coefficient that takes into account the dimensions of the part, which must be determined according of the regulations [6, 16],
- m – coefficient taking into account the state of the part surface.

In the European Union countries, the fatigue strength is assessed according to the acceptable stresses, and the permissible stresses are determined using limit stress diagrams. Two types of diagrams are used:

1. Diagrams given in the regulatory document (limit stress diagrams for various steel grades and type of part welded joints, obtained experimentally) [1, 4, 5, 15]. In these diagrams there is provided the dependence of the limit stresses (σ_{max} and σ_{min}) on the mean stress (σ_m) of the loading cycle.
2. Diagrams of limit stresses for welded steel structures [8] and welded aluminum and alloy structures [9]. These diagrams include data for steels from the European report ERRI B12/RP17-1997, but they significantly expand data on the types of welded joints. In addition, in these diagrams there is provided the dependence of the limit stresses (σ_{max}) on the coefficient of asymmetry of the lading cycle.

The examples of application of two types diagrams are show in the Fig. 1 and Fig. 2.

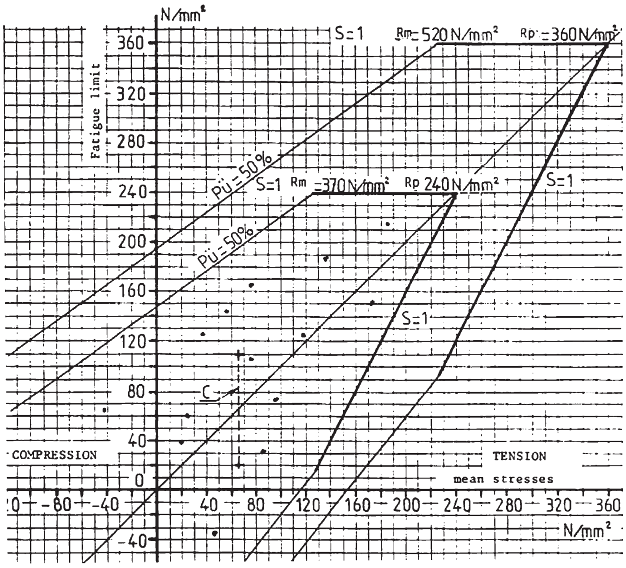

Fig.1. Assessment of fatigue strength using the limit stress diagram given in the report ERRI B12/RP17-1997 [Diagram is scanned]

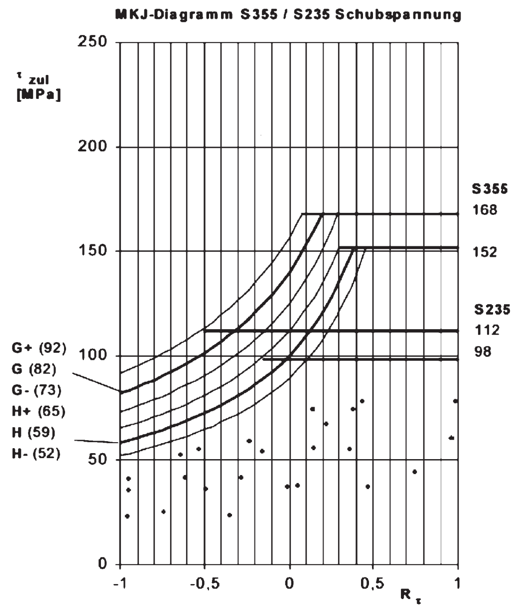

Fig. 2. Assessment of fatigue strength using the limit stress diagram is accordance with the requirements DVS 1612:2014-08 [Diagram is scanned]

The main advantage of using diagrams (Fig. 1 and Fig. 2) is the convenience of the results assessment. The strength of the structure is considered to be ensured if the stresses in the structure, obtained by calculation or experimentally, do not exceed the boundaries of the corresponding curves. For example, all the stresses (in Fig. 1 and Fig. 2 are shown by dots) are in the range of allowable values.

To compare the results of the assessment of fatigue strength according to European regulations and regulations applied in Ukraine, we should determine the limit stress of the loading cycle using Formula (1).

Maximum and minimum stresses of the stress cycle:

$$\sigma_{\max} = \sigma_m + \sigma_v , \quad (3)$$

$$\sigma_{\min} = \sigma_m - \sigma_v . \quad (4)$$

From Formula (1) it follows that:

$$\sigma_v = \left(\sigma_{-1} - n\psi\sigma_m\right)/nk = \sigma_{-1}/nk - \psi\sigma_m/k . \quad (5)$$

Upon substitution of expression (5) in (3) and (4), we obtain:

$$\sigma_{\max} = \sigma_{-1}/nk + \sigma_m\left(1 - \psi\sigma_m/k\right), \quad (6)$$

$$\sigma_{\min} = \sigma_{-1}/nk - \sigma_m\left(1 - \psi\sigma_m/k\right). \quad (7)$$

The limit stress diagrams of the loading cycle obtained with the use of relations (6) and (7) for grade steel 09Г2С with proportionality limit 345 MPa, as well as the limit stresses from the regulations ERRI B12/RP17-1997 for European steel 18G2A with yield strength 355 MPa are given in Fig. 3. Diagrams corresponding to the regulations [6, 16] are constructed at two values of the coefficient γ (see Formula 2), which takes into account the dimensions of the cross section of the part.

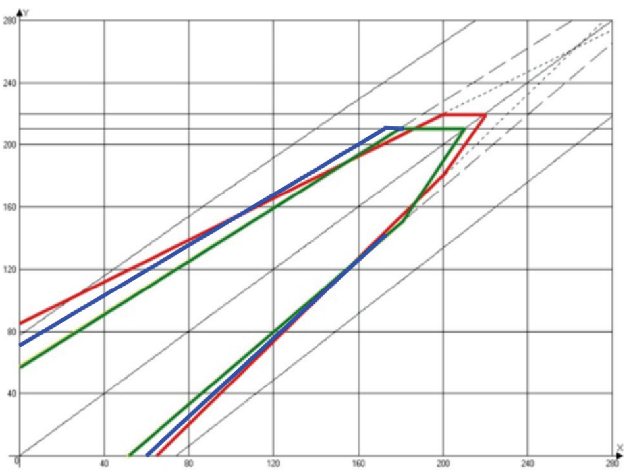

Fig. 3. Comparison of limit stress diagrams. The diagram, given in red, corresponds to European regulations, green and blue – to Ukrainian regulations with values of the coefficient γ equal to 0.6 and 0.8, respectively

It can be seen in Fig. 3 diagrams that the greatest discrepancy between the stresses of load cycles (green and red lines) occurs at a value of γ = 0.6 (the regulations [6, 16], the size of the part is 160 mm). This discrepancy is due, first of all, to the fact that in Ukrainian regulations the values of the coefficient γ are given depending on the diameter of the part, and not on the dimensions of its cross section. Or in other words, the recommendations of the regulations [6, 16] can be used for structural elements having circular cross-section.

The foregoing points to the need for special studies to determine the coefficient that takes into account the cross-sectional dimensions of parts, including parts made from rolled sections.

The most reliable results for determining the coefficient γ, taking into account the dimensions of the cross-section of the part, can be obtained using the relation:

$$\gamma = \frac{\sigma_{-1\partial}}{\sigma_{-1}} , \quad (8)$$

where:

- $\sigma_{-1\partial}$ – experimental value of the endurance limit of a part having a definite shape and dimensions of the cross section,
- σ_{-1} – experimental value of the endurance limit of a reference having circular cross section and made of the same steel grade.

Upon full-scale tests for the fatigue strength of the characteristic structural elements used in locomotive construction and having various shapes and sizes of cross section, a graph (graphs) similar to that given in the regulatory documents [8, 9] can be constructed. However, this way requires huge time and material costs and is currently impossible.

The main provisions on the theoretical definition of the scale factor were developed in the works of the well-known scientist in the field of fatigue strength of materials Kogaiev V.P. [3]. In the basis of Kogaiev V.P. development lies the statistical theory of fatigue failure. The basic equation for the similarity of fatigue failure obtained in [12] is as follows:

$$\frac{1}{\lg e}\lg\left(1-P\right) = \int\limits_{A_u}\left[\frac{\sigma\left(y\right)-u}{\sigma_0}\right]^m \frac{dA}{A_0} , \quad (9)$$

where:

- P – probability of occurrence of fatigue crack at stresses $\sigma \le \sigma_{-1\partial}$,
- $\sigma(y)$ – function describing the law of stress distribution over the height of the cross section $(0 \le f\left(x, y\right) \le 1)$,
- m – fatigue curve index,

u – minimum limit of the endurance limit (the probability of inequality $\sigma_{-1\partial} \le u$ is equal to 0). For plastic materials $u = 0.5\sigma_{-1}$,
σ_0 – scale factor,
A_0 – size factor.

The quantity that stands on the left side of the similarity Formula (9) is in fact the same probability of destruction of the part *P*. Thus, at $P = 0.05$:

$$\frac{1}{\lg e}\lg(1-P) = -2.3\lg(1-0.05) = 0.051,$$

at $P = 0.01$:

$$\frac{1}{\lg e}\lg(1-P) = -2.3\lg(1-0.01) = 0.01.$$

The integral on the right-hand side depends on the shape and dimensions of the section, and also on the law of distribution of normal stresses along its height. Calculation of this integral only for round and flat samples having different stress concentrators is described in papers [3]. Numerical data for rolled sections in these and other reference sources are not available.

Therefore, let's consider as an example a part made of a rolled section in the form of an I-beam (Fig. 4), whose normal stresses along the height are distributed according to linear law.

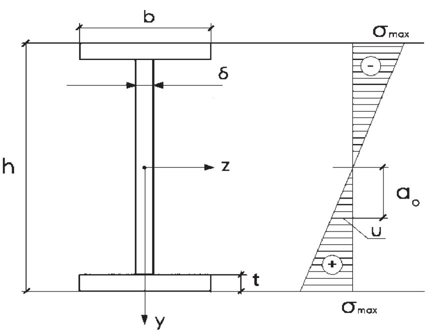

Fig. 4. Main dimensions of the rolled section in the form of I-beams: *h* – I-beam height, *b* – shelf width, *δ* – wall thickness, *t* – shelf thickness

Using the notations shown in Fig. 4, we can write the following relationship for determining the stress *σ* at the point located at the distance *y* from the section center of gravity:

$$\sigma - u = G(y - a_0), \quad (10)$$

where: *G* – gradient of normal stresses, calculated with the help of the following expression:

$$G = \frac{\sigma_{max} - u}{a - a_0},$$

where:
σ_{max} – is assumed to be equal to $\sigma_{-1\partial}$,
a – coordinates of the point, where the stresses are equal to σ_m, in our case it is $a = h/2$,
a_0 – coordinates of the point, where the stresses are equal to u, $a_0 = h/4$.

Taking into account the Formula (10) it is possible to write:

$$I = \int_{A_u} \left[\frac{\sigma - u}{\sigma_0}\right]^m \frac{dA}{A_0} = 2\int_{a_0}^{a} \left[\frac{G(y-a_0)}{\sigma_0}\right]^m \frac{bdy}{A_0}. \quad (11)$$

Upon integrating is obtained:

$$I = \frac{bh}{m+1}\left[\frac{u}{\sigma_0}\right]^m \frac{1}{A_0\xi}\left[(\xi-1)^{m+1} - c(d\xi-1)^{m+1}\right],$$

where:
c and d – parameters, depending on section size,
ξ – value equal to relation $\sigma_{-1\partial}/u$. In its turn, the value u for plastic materials is assumed to be equal to $0.5\sigma_{-1}$.

Parameters *c* and *d* are found from relation:

$$c = 1 - \frac{\delta}{b} \text{ and } d = 1 - \frac{2t}{h}.$$

In essence, the value ξ is desired size coefficient, since taking into account Formula (8) and the above value of *u*, we have:

$$\gamma = \frac{\sigma_{-1\partial}}{\sigma_{-1}} = \frac{\xi u}{\sigma_{-1}} = \frac{\xi \cdot 0.5\sigma_{-1}}{\sigma_{-1}} = 0.5\xi.$$

Thus, for the cross-section in the form of I-beam, Formula (9) after all the transformations becomes as follows:

$$\frac{1}{\lg e}\lg(1-P) = \\ = \frac{bh}{m+1}\left[\frac{u}{\sigma_0}\right]^m \frac{1}{A_0\xi}\left[(\xi-1)^{m+1} - c(d\xi-1)^{m+1}\right]. \quad (12)$$

The solution of the obtained similarity equation of fatigue failure can be obtained by the method of successive approximations or graphically. In case of graphical solution, there are points of intersection of the right and left parts of Formula (12), as a result, the required parameter ξ is determined. An example of a graphical solution is shown in Fig. 5.

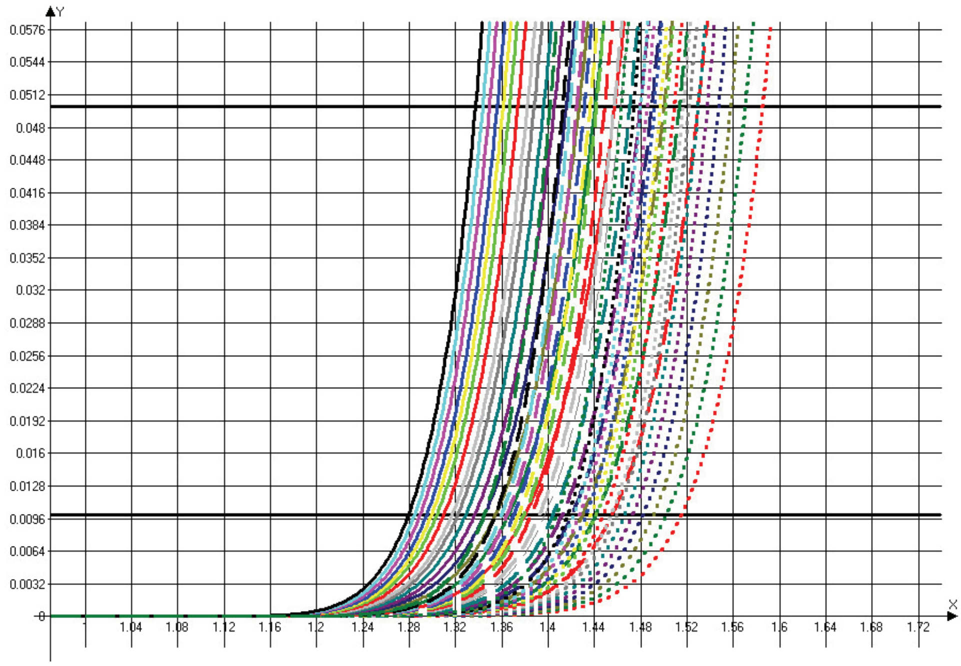

Fig. 5. Example of graphical solution of the fatigue failure similarity equation for I-beam

In the Fig. 5, the horizontal lines correspond to the probability of not destruction of the part 95% and 99%, each curve – to I-beam with a certain number and made of steel having the exponent of the fatigue curve *m*.

The results of solution of the Formula (10) for I-beams, channels and channel boxes (in accordance with GOST 8239-89) made from steels with different exponent of the fatigue curve *m* are given in Table 1. At calculation of *m* were taken into account 8, 10 and 12.

In the absence of experimental data, the exponent of the fatigue curve *m* according to GOST 25.504-82 should be determined from the ratio:

$$m = 5 + \frac{\sigma_B}{80},$$

where σ_B – ultimate strength of this steel grade in MPa.

Thus, for the abovementioned 09Г2C and 18G2A steels with strength limits of 480 MPa and 540 MPa, the fatigue curve should be taken equal to 11 and 12, respectively.

3. Calculation results

Using the method described above, the Author carried out calculations of the scale factor for rolled sections in the form of I-beam, channel, and channel box. According to the obtained results, the coefficient γ taking into account the dimensions of the part at calculation of the fatigue safety factor, varies within the following range:

1) I-beam – $0.69 \le \gamma \le 0.75$,
2) channel – $0.7 \le \gamma \le 0.77$,
3) channel box – $0.69 \le \gamma \le 0.76$.

Taking into account the foregoing, it is proposed to add the data of Table 2 to the developed in Ukraine Regulations on design and assessment of locomotive and multi-unit strength.

Table 2

Values of coefficient γ, taking into account the dimension factor influen

Part section height [mm]	Coefficient γ value
up to 100	0.8
100–250	0.75
more than 250	0.7

Table 2 is fully consistent with relevant table, given in GOST 33796-2016, applicable in all the 1520 mm gauge countries, except Ukraine.

4. Conclusions

1. In order to avoid conflict situations when carrying out certification tests of rail vehicle manufactured by EU countries in Ukraine and vice versa, it is necessary to harmonize requirements of fatigue strength for 1520 mm and 1430 mm.
2. The implementation of the scale factor values in the Ukrainian regulations proposed by Authors

of this article will allow harmonizing the requirements for assessment of strength of load-bearing structures of locomotives and multi-unit fatigue strength with the requirements of similar regulatory documents applicable in the EU countries.

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Ocena wytrzymałości zmęczeniowej lokomotyw i zespołów trakcyjnych z uwzględnieniem wyników badania certyfikacyjnego na Ukrainie i w krajach UE

Streszczenie
W artykule przedstawiono analizę porównawczą metod oceny wytrzymałości zmęczeniowej pojazdów szynowych eksploatowanych na Ukrainie i w krajach UE. Wyróżniono następujące istotne różnice w opisanych metodach:
1. Na Ukrainie, ocena wytrzymałości zmęczeniowej prowadzona jest przy użyciu wskaźnika wytrzymałości zmęczeniowej, który nie powinien przekraczać wartości normatywnej. W krajach Unii Europejskiej, wytrzymałość zmęczeniowa jest oceniana w zależności od poziomu dopuszczalnych naprężeń określanych z wykresu naprężeń i odkształceń.
2. Zgodnie z wymaganiami norm na Ukrainie, do określenia wskaźnika wytrzymałości zmęczeniowej wykorzystuje się granice wytrzymałości standardowych próbek przy symetrycznym obciążeniu. Wykresy granic na-

prężenia używane w europejskich normach, są konstruowane dla charakterystycznych elementów konstrukcyjnych z uwzględnieniem współczynników niesymetrycznego cyklu naprężenia.
Przeprowadzone przez autora studia teoretyczne i analiza danych doświadczalnych, umożliwiły opracowanie rekomendacji mających na celu podniesienie jakości oceny wytrzymałości zmęczeniowej konstrukcji nośnych elementów taboru z własnym napędem i przygotowanie propozycji zharmonizowania odpowiednich dokumentów regulacyjnych na Ukrainie i w krajach UE.

Słowa kluczowe: lokomotywa, zespół trakcyjny, certyfikacja, wytrzymałość zmęczeniowa, kryteria oceny

Оценка усталостной прочности локомотив и самоходных подвижных составов согласно результатам сертификационных тестов в Украине и странах ЕС

Резюме
В статье представлен сравнительный анализ методов оценки усталостной прочности единиц железнодорожного подвижного состава использованых в Украине и странах ЕС. В результате упомянутого сравнения были выделены важные разницы в описаных методах:
1. В Украине оценка усталостной прочности проводится при употреблении индикатора усталостной прочности, который не должен превышать нормативного значения. В странах ЕС усталостная прочность оценивается соответственно уровню допускаемого напряжения, а допускаемое напряжение определяется при помощи диаграммы напряжения-деформации.
2. Согласно требованиям норм в Украине, для определения фактора усталостной прочности используется пределы прочности стандартных образцов при симметричной нагрузке. Диаграмы пределов напряжения используемые в европейских нормах сконструрированы для характеристических конструкционных элементов с учетом коэффициентов несимметричного цикля напряжения.
Проведенные автором аналитические разработки и анализ экспериментальных данных сделали возможным разработку ряда рекомендаций направенных на повышение надёжности результатов оценки усталостной прочности несущей конструкции самоходных единиц подвижного состава и подготовку предложений регуляционных документов в Украине и странах ЕС.

Ключевые слова: локомотива, моторвагонный поезд, сертификация, усталостная прочность, критерия оценки