Justification of Safe Operation of Rolling Stock by the Lifetime of Its Bearing Structures

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Abstract. The problem of providing strength and reliability of rolling stock bearing structures which include welded and cast parts of bogie frames and bodies of cars and locomotives, as well as brackets and attachment points for their equipment and traction drive units, is one of the most important in the design, construction and operation. The development of high-speed and heavy-haul traffic, as well as the introduction of requirements for determining the design service life and lifetime of railway transport facilities, make the above task even more urgent. The influence of the operational loading characteristics of the object on the safety factor of fatigue strength and its depletion: amplitudes of cyclic stresses, frequencies of their change, parameters characterizing the intensity of the rolling stock operation (number of loading cycles, speed of movement, average daily mileage) is shown based on the results of computational and experimental studies carried out with running dynamic and strength tests of locomotives at all operating speeds of their movement in operation.

1. Introduction
To ensure the operation of railway equipment parts and structures without damage during a given service life, the current regulatory documents [1–4] provide for estimation their strength based on deterministic methods by permissible stresses and safety factors in relation to the yield strength \(\sigma_{0.2}\) = 1.0...1.2, preventing the occurrence of residual strains, and to the part endurance limit \(n_{\sigma_{0.1}} = 1.5...2.0\), preventing cracks initiation in elements. However, this does not to the full extent take into account the random nature of the operating loads, under the influence of which the accumulation of fatigue damage occurs, and does not allow to estimate the service life and to judge the probability of structural failure or the degree of such risk during the service life. At the same time, in the rail transport sphere these values, along with strength and reliability, will become critical in the near future, especially for heavy-haul and high-speed traffic.

2. Theoretical background
From the point of view of the influence of the mechanical structures safety on the state of the transportation process, the theory of damage accumulation during random overloads, developed by V.V. Bolotin [5], is the most widely used. According to this theory, the failure of a structure occurs as a result of the gradual damage accumulation, residual strains, wear, etc., which, having reached a certain value, begin to prevent the normal operation of the structure. In other words, a properly designed structure has
such a safety margin that for the given parameters of the random process of repeated-variable loading by the end of the specified service life, it is characterized by the probability of transition to an unacceptable limit state not exceeding a given value. Finally, this probability depends on the intensity of consumption of the safety margin as strains, wear and cracks accumulate. Obviously, when the operating conditions of the structure (object) change, for example, when the weight or the speed is reduced, it is possible to postpone the transition period of the structure to the limit state.

As shown by theoretical studies and operating experience of railway facilities, there is a tight relationship between the safety factor of fatigue strength, levels of cyclic stresses and the operation time or the intensity of operation (in load cycles, kilometers of run, hours of operation) [6, 7]. The basic concepts and definitions of the safe operation life time of objects make it possible to compare and interconnect their governing parameters for following analysis, justification, regulation and life time management.

The safety factor of the fatigue strength of the part $n_\sigma$ when using the probabilistic method with the construction of histograms of the distribution of the stress amplitudes current values $\sigma_{ai}$ under the conditions of rolling stock operation [1, 2, 4] is determined from the ratio:

$$n_\sigma = \frac{\sigma_{-1i}}{\sigma_{ay}},$$

where $\sigma_{-1i}$ is the part endurance limit under a symmetric loading cycle, determined for a given probability of non-failure $P \geq 0.95$ depending on the quantile of the normal distribution $U_P$ [8] and the coefficient of variation $\nu$ according to the formula $\sigma_{-1i} = \bar{\sigma}_{-1i}(1 - U_P \nu)$ as a result of the part bench fatigue tests based on $N_0 = 10^7$ cycles with the construction of the fatigue curve and the definition $\bar{\sigma}_{-1i}$, which is taken as the average (median) value of the endurance limit; $\sigma_{ay}$ is the amplitude (equivalent) of dynamic stresses in the part, is determined by statistical processing of schematized random processes of stress changes at all operating speeds of rolling stock movement according to the formula [1, 2]:

$$\sigma_{ay} = m \sqrt{\frac{N_0}{N_0 \sum P_{vi} \cdot \sigma_{ai} \cdot P_{ai}}},$$

where $m$ is the slope of the fatigue curve; $N_0$ is the total number of cycles of dynamic stresses during the service life (operation time); $P_{vi}, P_{ai}$ are fractions (probabilities of occurrence) of movements and stress amplitudes in the corresponding intervals of speeds in operation.

3. Application example

For example, the normative value of the safety factor $n_\sigma = 2.0$ [2, 3] in the designs of locomotives and multiple units is provided at stress amplitude levels $\sigma_{ay} = 20…25$ MPa and operation time $N_0 = 5 \cdot 10^6$ cycles. With an increase in the intensity of operation or operation time $N_0$, for example, in $K = 2…3$ times, under otherwise equal conditions, the stress equivalent to this operation time in damaging action will increase by $\sqrt{K}$, and the safety factor $n_\sigma$ will decrease by the same amount, which will characterize its loss or life time consumption. Examples of the calculated dependences of these parameters are shown in Fig. 1.

It follows from the above that the normative values of the safety margins of bearing structures in the design of railway transport facilities should be established taking into account the loading parameters and life time at the stages of the life cycle. Thus, ensuring the reliability and safety of operation of critical structures of railway equipment dictates the need to estimate the depleted life time in hazardous zones of structural elements and analyze the rate of damage accumulation and the life time depletion in these zones during operation.
Figure 1. Dependence of the safety factor of fatigue strength $n_\sigma$ and the stress amplitudes $\sigma_{aeq}$ equivalent in terms of the damaging effect on the total operation time $N_\Sigma$ in the zones of the most loaded elements 1 and 2 of the diesel locomotive bogie frame structure.

4. Conclusion
The modern development of the fundamental theory of life time and safety necessitates the improvement of the existing traditional approaches to ensuring the required conditions for the safe operation of high-risk objects. They should be based on specified parameters of life time, safety and risks, justified by the criteria of strength and reliability.

5. References
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