Estimation of minimal damaging stresses under cyclic loading of steel riveted bridge spans

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Abstract. The article presents the results of studies on the assessment of the value of the minimum damaging stresses during cyclic loading of steel riveted spans of railway bridges. A gradual accumulation of irreversible distortions of the crystal lattice of steel in the zone of riveted holes during the service life of the span was experimentally established. Cyclic loading of low-carbon steel at stresses below the endurance limit and above the cyclic elastic limit leads to the formation of submicrocracks in the metal structure, which ultimately reduces its vitality and affects the accelerated formation of microcracks at stresses exceeding the endurance limit.

When calculating the durability and residual fatigue life of steel superstructure elements, one should take into account those total stresses from constant and temporary loads that exceed the fatigue limit of the considered type of bridge structure connection. In this case, the limiting value of fatigue damage ν_{lim}, accumulated by a certain element of the truss when exposed to heavy train loads, should be taken equal to 0.3 when summing these damages in accordance with the Palmgren - Miner hypothesis

Keywords: railway bridges, steel, spans, cyclic loading, submicrocracks, fatigue, endurance limit

State of the issue

Endurance tests of steel samples without stress concentrators cut from different elements of span structures, which were in operation for 70 to 100 years, did not reveal any fatigue damage to the base metal during the operation of bridge structures [1]. The values of the endurance limit of the studied steel grades correspond to the analogous characteristics of modern steel grades of the same strength class. The results of endurance tests of metal with stress concentrators in the form of holes do not find a satisfactory explanation based on the commonly used hypothesis of fatigue damage accumulation in spans at stresses below the fatigue limit. It should be noted that there is a contradiction between the actual fatigue life of the operated steel bridge spans and its calculated value determined according to the Guidelines [2]. To set the timing of replacement of such structures, it is necessary to have a more reliable methodology for assessing the residual life of superstructures, especially in the case of commissioning heavier train loads. It is necessary to clarify the dependence of the durability of bridge elements on the nature of their loading and, in particular, on the value of the minimum stresses that cause fatigue damage to steel spans.

Analysis of the test results of the metal of the superstructure taken out of service

The results of endurance tests of specimens cut from a fragment of the lower belt of the superstructure with a length of 65.88 m, presented in article [1], are shown in figure 1.

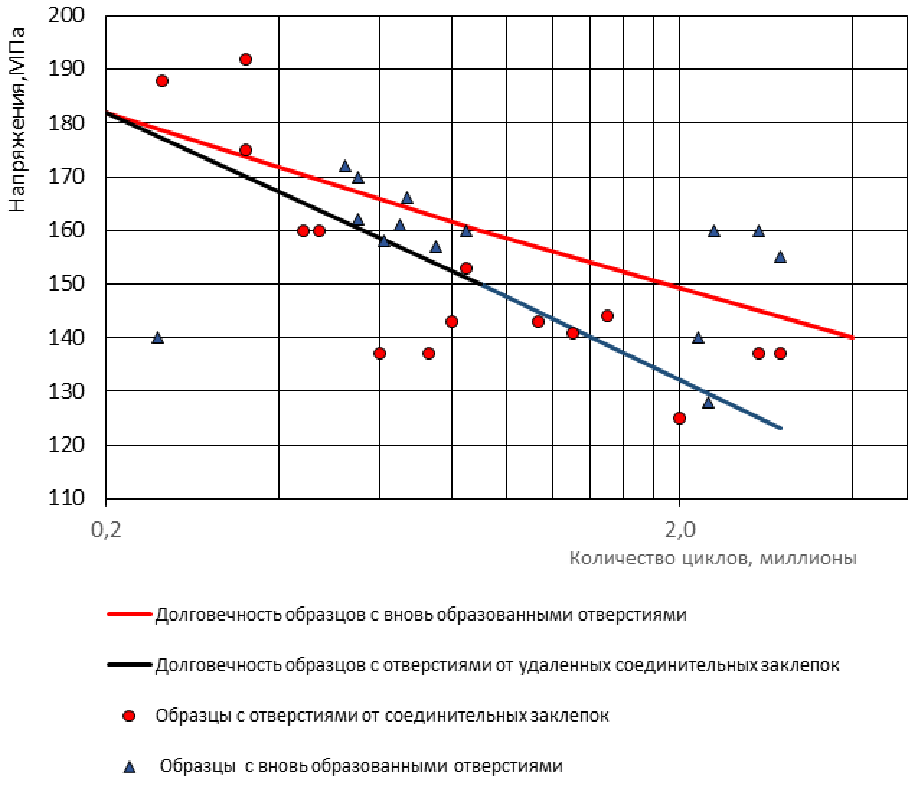

Figure 1 – Durability of perforated steel specimens

The data presented indicate that specimens with holes from connecting rivets in comparison with specimens of the same metal with newly formed holes at a loading level above the fatigue limit have a lower durability, i.e. lower survivability k = tgφ. This result is explained by the gradual accumulation of irreversible distortions of the crystal lattice of steel in the zone of riveted holes during the service life of the span structure [3]. To assess the dependence of possible distortions of the crystal lattice of the metal of the elements of superstructures on their stress state when loaded with train loads, the value of the calculated stresses in the element of the lower chord of the superstructure with a length of 65.88 m (design standards 1907), the metal of which was studied, was determined. As train loads, four models of the heaviest freight trains and one of the passenger trains were selected, which had been circulating across the bridge for 80 years. Four-axle freight gondola cars and tanks were modeled with a distributed load of 7.2 t/m, passenger cars - with a load of 2.8 t/m. The types of locomotives used in the models of train loads are shown in Table 1. For a comparative assessment of the effect of the considered types of loads on the endurance of a superstructure element, the calculated stresses σ_{-1} are reduced to one characteristic of the cycle ρ = -1 in accordance with the relationship [4]:

$$\sigma_{-1} = \frac{\sigma_B \sigma_\rho (1-\rho)}{(\sigma_B - \sigma_\rho \rho) - (\sigma_B - \sigma_\rho)(-1)} \tag{1}$$

where σ_B – temporary resistance of the considered steel grade, σ_ρ – maximum stresses in the superstructure element at the cycle characteristic *ρ*.

Table1 – Design stresses (MPa) in the lower chord of a truss with a length of 65.88 m under the influence of train loads

Stress type, MPa	Train load type				
	"FD" +7.2 t/m	"L" +7.2 t/m	"FDp" +2.8 t/m	"E" + 7.2 t/m VL80 + 7.2 t/m	Vl22 +7.2 t/m
From temporary load, taking into account dynamic impact	70.7	68.7	57.7	63.6	64.0
From constant load	33.3	33.3	33.3	33.3	33.3
Maximum calculated	104.0	102.0	91.0	96.0	97.3
Cycle asymmetry coefficient *ρ*	0.317	0.324	0.363	0.346	0.343
Reduced to a symmetric cycle *(ρ = -1)*	42.8	41.5	34.5	37.5	38.1

The calculated values of the endurance limits of these steel grades at various effective stress concentration factors β are given in Table 2. For the calculation, β values equal to 1.3 and 3 were taken, reflecting the ratio of the endurance limits of the base metal and, accordingly, elements with connecting rivets and attachments of structural elements to knot gussets with single-cut rivets [2]. Table 2 shows the calculated values of the cyclic elastic limit $\sigma_{ц}^{e}$ [3].

Table 2 – Values of endurance limit and cyclic elastic limit depending on steel grades and values of the effective stress concentration factor

Steel grade	Endurance limit, MPa				Cyclic elastic limit, MPa		
	base metal		compounds at ρ=-1		base metal	connections	
	ρ = 0.1	ρ = -1	β = 1.3	β =3.0	β =1.0	β =1.3	β = 3.0
0.8 kp	243.8	163.0	125.4	54.3	103.0	65.4	0
St.3 kp	207.0	125.9	96.8	42.0	65.9	36.8	0
St.0	180.0	108.6	83.5	38.3	48.6	23.5	0

Metallographic analysis of samples made of steel St.3kp made of the element of the lower chord of the truss, which were not subjected to laboratory endurance tests, in the area of the holes from the remote connecting rivets did not reveal significant signs of aging and work hardening of the metal, however, an increase in the microhardness of the steel was noted. In a number of works, a review of which is given in [3], it is shown that in the zone of possible formation of fatigue damages under certain conditions, the microhardness of local volumes of steel increases during cyclic loading.According to [3], an increase in metal hardness under cyclic loading occurs at stresses exceeding the cyclic elastic limit $\sigma_{\text{ц}}^{e}$, the value of which is less than the fatigue limit under a symmetric loading cycle σ_{w} by about 60 MPa. In this case, in the stress range from $\sigma_{\text{ц}}^{e}$ to σ_{w} under cyclic loading, a gradual formation of submicroscopic cracks occurs, which, with an increase in alternating stresses above the endurance limit σ_{w} gradually develop into macrocracks.

Comparison of the data in Tables 1 and 2 shows that the values of the maximum stresses in the superstructure with a length of 65.88 m from the impact of heavy train loads exceed the value of the cyclic elastic limit of steel St.3kp in the stress concentration zones near holes with connecting rivets. Thus, in the indicated local zones, a gradual formation of submicrocracks occurred, which was the basis for the accelerated growth of macrocracks during laboratory tests with increasing loads and a corresponding increase in stresses exceeding the endurance limit of such joints. At the same time, the effects of passenger and empty freight trains could not lead to irreversible changes in the structure of the metal in such zones of stress concentration.

The linear hypothesis of the accumulation of fatigue damage by elements of bridge structures is applicable with alternating loading cycles with different levels of impact. With a gradual increase in the level of stresses in the metal from alternating loads, the accumulation of fatigue damage does not correspond to a linear law. Cyclic loading of low-carbon steel at stresses below the endurance limit and above the cyclic elastic limit leads to distortion of the crystal lattice and the formation of submicrocracks in the metal structure, which ultimately reduces its vitality and affects the accelerated formation of microcracks at a stress level exceeding the endurance limit.

Test results of steel samples under non-stationary loading conditions

The obtained data are confirmed by the results of endurance tests of three series of specimens under step loading conditions. The studies were carried out on flat specimens made of St.3 steel with stress concentrators in the form of a round hole in the center of each specimen. For the subsequent analysis of the test results under stepped loading conditions, the same specimens were first tested under stationary modes with a cycle characteristic ρ = 0.1 (series 1). The endurance limit of these samples at ρ = 0.1 was 167.5 MPa with a fracture probability of 50%. Two or three-stage loading modes of samples reflect the tendency of changes in the stress state of certain elements of the main trusses of the operated span structures with an increase in linear train loads from 7.2 to 12 t/m. As a result, the first steps of loading the samples were carried out at stresses below their endurance limit. The loading parameters of the samples and the test results are shown in Figure 2.

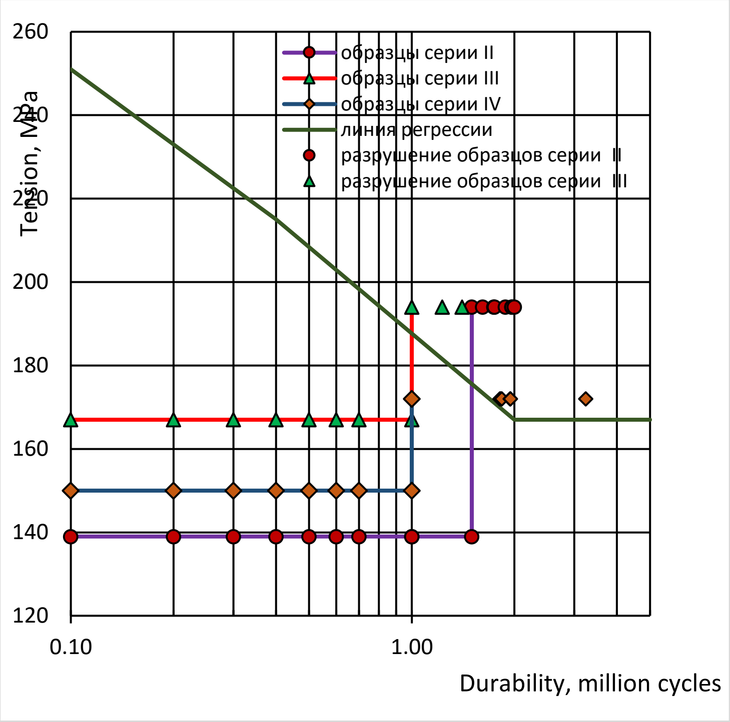

Figure 2 – Results of endurance tests of specimens with a hole under stepped loading conditions

Table 3 shows the number of loading cycles of specimens to the moment of their failure and accumulated fatigue damage calculated by formula (2) based on the linear hypothesis of their accumulation (Palmgren - Miner hypothesis) at a 50% probability of failure

$$\nu = \Sigma \frac{n_i}{N_i} \le \nu_{np} = 1 \tag{2}$$

In formula (2), n_i denotes the number of loading cycles of the sample at a certain stress level; N_i is the limiting number of loading cycles at the same stress level that the sample can withstand until failure under constant cyclic action. The average value of the sum of damages accumulated by the tested samples at the last stage of loading at stresses above the endurance limit is 0.4.

Analysis of the obtained results

The above results are confirmed by earlier studies [5], showing that the accumulation of fatigue damage in low-carbon steel depends on the history of its loading. The linear hypothesis of the accumulation of fatigue damage by elements of bridge structures is applicable with alternating loading cycles with different levels of impact. With a gradual increase in the level of stresses in the metal from alternating loads, the accumulation of fatigue damage does not correspond to a linear law. Cyclic loading of low-carbon steel at stresses below the endurance limit and above the cyclic elastic limit leads to distortion of the crystal lattice and the formation of submicrocracks in the metal structure, which ultimately reduces its vitality and affects the accelerated formation of microcracks at a stress level exceeding the endurance limit. Taking into account the requirements for the reliability of bridge structures, the limiting value of fatigue damage ν_{lim}, accumulated by a certain element of the truss under the influence of heavy train loads should be taken equal to 0.3 when summing these damages in accordance with the Palmgren - Miner hypothesis.

Of the three steel grades considered, lower fatigue resistance is characteristic of steel St.0 with a yield strength of 212 MPa. At the same time, in the area of holes for connecting rivets in the most loaded elements of trusses made of this steel, practically all types of circulating train loads caused the gradual formation of submicrocracks. At the same time, in the manufacture of the same elements from steel 08kp, all other conditions being equal, submicrocracks should not appear in the zone of the indicated holes. However, in the nodal joints with single-shear rivets of the most stressed elements of the main trusses made from the considered steel grades, freight trains circulating on the railways of Russia in the twentieth century caused the formation of submicrocracks in the metal along the edges of the rivet holes. As a result, the commissioning of freight cars with linear loads of the order of 8-10 tf/m and higher will contribute to the accelerated formation of fatigue damage in joints with single-shear rivets.

Conclusions

1. The above research results show that the possibility of fatigue failure of elements of operated steel spans and preliminary formation of submicrocracks in individual zones of joints of

bridge structures is influenced by both the properties of the steel from which the bridge structure is made and the stress state of individual sections of the elements, determined by their type, size the concentration of stresses in the connections of the elements and the effect of the train load.

2. When calculating the durability and residual fatigue life of steel superstructure elements, one should take into account those total stresses from constant and temporary loads that exceed the fatigue limit of the considered type of bridge structure connection.

3. In the nodal joints with single-shear rivets of the most stressed elements of the main trusses, freight trains circulating on the railways of Russia in the 20th century caused the formation of submicrocracks in the metal along the edges of the rivet holes. Innovative freight cars with linear loads of the order of 8-10 tf/m will cause higher stresses in nodal joints with single-shear rivets than circulating trains, and, as a result, contribute to accelerated formation of fatigue damage in the zones of riveted holes. In this case, the limiting value of fatigue damage ν_{lim}, accumulated by a certain element of the truss when exposed to heavy train loads should be taken equal to 0.3 when summing these damages in accordance with the Palmgren - Miner hypothesis.

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