Results of metal endurance tests of bridge spans that have been in operation

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Abstract. The article presents the results of endurance tests of steel samples cut from the elements of spans that have been in operation for more than 70 years. Samples for endurance tests were made from fragments of the lower chords of the main trusses and the webs of the longitudinal beams of the carriageway of the replaced superstructures.

The results of endurance tests showed that the durability of a certain steel grade is proportional to the yield point of the metal and practically does not depend on the service life of the bridge structure at the value of maximum stresses in the elements of superstructures from constant and train loads up to 120 MPa. The linear hypothesis of the accumulation of fatigue damage in the elements of operating spans at a stress level below the fatigue limit of the connection under consideration cannot be used to assess the durability and residual life of steel bridge structures.

Keywords: Railway bridges, spans, steel, stress concentration, endurance, fatigue, damage accumulation

State of the issue

The article [1] shows that the strength capacity of steel superstructures, designed according to the standards of 1907-1932, is sufficient to handle promising train loads with an intensity of up to 10.5 tf/m track. At the same time, the fatigue resistance of these spans, which have a service life of more than 70 years, in the case of an increase in linear train loads, has not been studied enough. Calculations for the assessment of the fatigue life of the elements of the main trusses of the operated steel superstructures, performed 30 years ago in accordance with the Guidelines [2], showed that a number of bridge structures built at the beginning of the XX century should have exhausted their fatigue life as early as 1985-1999 years. At the same time, a survey of span structures carried out by employees of the Research Institute of Bridges 10 years ago did not confirm the presence of any fatigue damage in the elements of the inspected riveted structures, which, according to the forecasts mentioned, should have already had such damage.

At the same time, previously conducted surveys of operated bridges of old construction years revealed fatigue failures in individual elements of lattice girders [3,4]. To develop an optimal strategy for the maintenance and replacement of operated steel spans, it is necessary to accumulate data on the state of the metal of the spans of the design of the late 19th - first half of the 20th centuries, the mechanical characteristics of which are often unknown at the delivery stage. Information on the fatigue resistance of the metal of the span structures of these bridges, on the possible accumulation of fatigue damage in the zones of stress concentration in the elements and nodes of bridge structures is important.

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. An urgent task is to clarify the dependence of the durability of bridge elements on the nature of their loading and, in particular, on the magnitude of the minimum stresses that cause fatigue damage to steel spans.

Formulation of the problem

To study the mechanical characteristics of the metal of the operated steel spans and its durability, elements of the replaced spans of bridges of various years of construction were selected. Brief information about the spans from which the samples were cut and the mechanical characteristics of the steel grades used for their manufacture are given in table 1.

Table 1 – Information on spans and characteristics of steel grades used for their manufacture

Truss span length, m	Design standards, year/year of construction of the bridge	Truss life in years	Tonnage passed over the period of operation million tons km	Structural elements from which samples are cut	Thickness of sheet metal-roll, mm	Steel grade according to the results of chemical analysis	Mechanical characteristics of metal, MPa	
							Temporary resistance	Yield point
44.5	1896/ 1897	105	1510	Truss bottom belt	10	St.0	410	212
106.68	1907/ 1912	90	1340	Longitudinal beam wall	10	St.0	465	269
87.0	1907/ 1916	85	2650	Longitudinal beam wall	10	St.3 kp	438	230
87.0	1907/ 1916	85	2650	Truss bottom belt	11,9	St.0	465	269
65.88	1907/ 1923	80	2000	Longitudinal beam wall	10	08 kp	410	276

65.88	1907/ 1923	80	2000	Truss bottom belt	11,9	St.kp	438	230
87.6	1925/ 1931	72	2370	Truss bottom belt	10	Cast iron	370	218

Samples for endurance tests were made from fragments of the lower chords of the main trusses and the webs of the longitudinal beams of the carriageway of the replaced superstructures. The durability of both the base metal and the samples with stress concentrators in the form of round holes was investigated. To assess the accumulated fatigue damage in the hole zones from the rivets, several series of samples were made. The manufacture of samples with stress concentrators in the form of rivet holes was carried out as follows. The heads of the connecting rivets from the side of the corners were cut off by autogenous, after which the remaining parts of the rivets were knocked out with a punch. After removing the rivets, the parts of the fragments of the lower chords were separated from each other. Then, on a milling machine, a disk cutter from horizontal sheets was used to cut samples to size.

Samples of series 1 were strips 260 mm long, 70 mm wide, and 11 and 9 mm thick. After cutting, the width of the samples decreased to 52 mm. In the middle of each specimen, there was a hole 20 mm in diameter from the remote rivet. During operation, this hole was filled with a connecting rivet. These holes were not subjected to any mechanical processing, i.e., the conditions under which the metal worked in the structure during its operation were preserved. Samples of series 2 were cut from the middle part of horizontal sheets of truss chords, where there were no connecting rivets. They also consisted of strips 260 mm long, 70 mm wide, and 11 and 9 mm thick. After cutting out the strips, their width decreased to 52 mm, and a hole with a diameter of 20 mm was drilled in the center of each sample.

The shape and dimensions of the samples of these series were taken in accordance with GOST 25.502-79. The samples were made from plates cut by autogenous from the walls of the longitudinal beams or from vertical sheets of fragments of the lower chords. Cutting of blanks from the plates was carried out with a disk cutter. The same plates were used to make strips for standard mechanical tests.

Fatigue tests of the samples were carried out on a TsDM-10 PU press-pulsator with a frequency of 1000 cycles per minute on the basis of 3 million cycles. When testing all series of samples, the cycle asymmetry coefficient was taken equal to 0.1 ($\rho = 0.1$). Determination of stresses in the samples was carried out according to the readings of strain gages using a strain gauge control system.

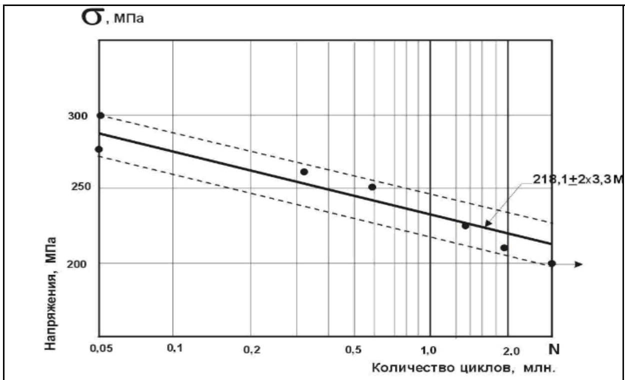
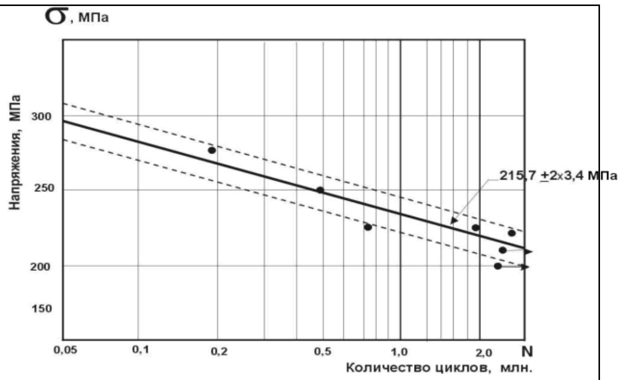
Laboratory test results

Table 2 shows the limited endurance limit values of $\sigma_{0.1}$ (based on 2 million load cycles) for all tested series of samples.

Table 2 – Limited endurance limits of tested specimens

№ sample series	Span length, m	Superstructure element	Steel grade	$\sigma_{0,1}$, MPa
1	87.0	Horizontal sheets of the lower chord of the main truss (holes after rivets removed)	St. 0	105.5
2		Horizontal sheets of the lower chord of the main truss (newly formed holes)	St. 0	155.6
3		Longitudinal beam wall (stretched zone)	St.3 kp	218.1
4		Longitudinal beam wall (at the neutral axis)	St.3 kp	215.7
5	44.5	Main truss bottom chord vertical sheet	St. 0	198.1
6	65.88	Longitudinal beam wall (stretched zone)	08 kp	243.8
7		Horizontal sheets of the lower chord of the main truss (holes after rivets removed)	St.3 kp	131.2
8		Horizontal sheets of the lower chord of the main truss (newly formed holes)	St.3 kp	151.2
9	106.68	Longitudinal beam wall (stretched zone)	St. 0	233.4
10	87.6	Vertical sheets of the lower chord of the main truss (holes after rivets removed)	Cast iron	133.6
11		Main truss bottom chord vertical sheets (newly formed holes)	Cast iron	150.6

As can be seen from Table 2, the endurance limits $\sigma_{0.1}$ of the series of samples with holes from the connecting rivets turned out to be lower than the endurance limits of the series of samples with newly formed holes. Since the samples of these series were made from the same fragments of the lower chords of the main trusses of the span structures, the decrease in the durability of the samples with holes from the connecting rivets can be explained by the change in the metal structure in the zones of the riveted holes that occurred over the years of operation of the bridges. It should be noted that the values of the endurance limits of samples of series 3, cut from the stretched zone of the longitudinal beam wall, and samples of series 4, cut from the zone near its neutral axis, turned out to be very close. The difference between them is practically within the scatter of experimental data (figures 1, 2).

 Figure 1 – Base metal from the tensioned zon the longitudinal beam wall. Series 3	 Figure 2 – Base metal from the zone of the neu axis of the longitudinal beam. Series 4

To analyze the data obtained, a calculated assessment of the stress state of that zone of the longitudinal beam wall from which the tested samples were cut was performed (Table 3). The stresses in the wall from the considered loads are in the range from 80 to 122 MPa, or from 31.1 to 58.5 MPa with an equivalent symmetric loading. This indicates that alternating stresses with amplitudes of up to 58.5 MPa under a symmetric loading cycle have practically no effect on the accumulation of fatigue damage in steel, i.e. there are no significant structural changes in the metal that affect its durability.

Table 3 – Design stresses (MPa) in the web of the longitudinal beam in the interface zone with the upper chord under the influence of train loads

Stress type	Train load types					
	Steam locomotives		Electric locomotives		Linear load from wagons, tf/m track	
	«L»	«E»	Vl22	VL80	7.95	7.2
From constant load	24.75	24.75	24.75	24.75	24.75	24.75
From temporary load, taking into account dynamic impact	97.67	96.89	80.45	54.71	97.40	80.45
Maximum calculated	122.4	121.6	105.2	79.46	122.15	105.2
Cycle asymmetry coefficient ρ	0.20	0.20	0.235	0.311	0.20	0.235
Reduced to a symmetric cycle (ρ = -1)	58.5	58.3	47.2	31.1	58.4	47.2

For a comparative assessment of the impact on the endurance of a superstructure element of the considered types of load, the calculated maximum stresses are reduced to one characteristic of the cycle ρ = -1 in accordance with the relationship [5]:

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

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

The results of vibration tests of the base metal of the above spans also showed that the durability of cast iron specimens without stress concentrators is at the level of durability of similar specimens from modern low-carbon steels, which is consistent with the results of previous studies [6, 7].

Analysis of the obtained results

Let us analyze the test results of samples cut from horizontal sheets of the lower chord of the superstructure with a length of 65.88 m (series 7 and 8, Figures 3 and 4). The regression line equation describing the dependence of the durability of samples with holes on remote rivets is as follows:

$$N=10^{27,377-9,872\lg\sigma_\rho} \tag{2}$$

Here σ_ρ - maximum stresses in the element under consideration at the cycle characteristic ρ, N – the corresponding durability of the element.

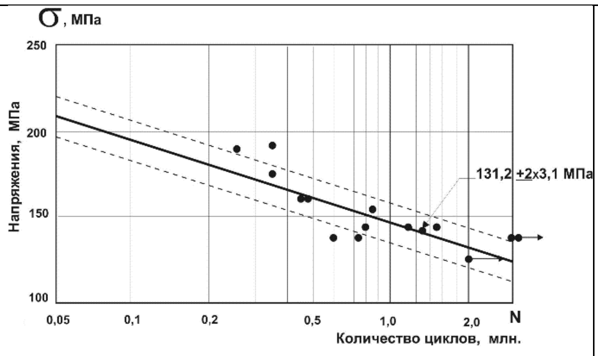


Figure 3 – Samples with holes from removed rivets. Series 7

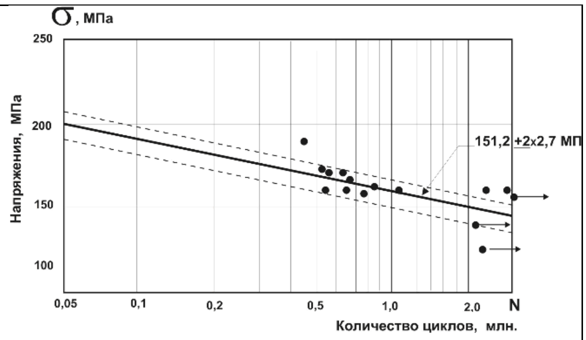


Figure 4 – Samples with newly formed holes. Series 8

The regression line equation describing the dependence of the durability of samples with newly formed holes is written as:

$$N=10^{30,671-11,186\lg\sigma_\rho} \tag{3}$$

Let us estimate the calculated durability of these samples at the stress level in the considered element of the lower chord at the stage of operation of the superstructure with a length of 65.88 m, assuming that the relationship between the durability of the metal and its stressed state remains at any stress level. The live load is taken in the form of a train consisting of a steam locomotive of the "L" type and a wagon load with an intensity of 7.2 tf/m track. The constant load is taken according to the Guidelines [2]. Reduced to the characteristic of the cycle ρ=0.1 (formula 1), the maximum design stresses in the lower belt are 68.7 MPa. At this level of stresses, the durability of the metal of the lower chord in the zones of holes from the connecting rivets will be 1557.5 million cycles, and of the metal with newly formed holes - 11,650 million cycles. The difference between the given values of the durability is about 10 billion cycles. As the experience of operating railway bridges shows, during the service life of the superstructure, no more than 2 million trains pass through it, including not only heavy freight, but also empty, as well as passenger trains. About one million trains have passed over the bridge under consideration during the operation of the superstructure. If we accept the commonly used hypothesis that fatigue damage in the elements of spans accumulates at any stress level in accordance with the dependence described by the regression line constructed during metal testing at sufficiently high stresses on the basis of 2 million cycles, then with this approach to the assessment the accumulation of fatigue damage in the elements of the main trusses of the superstructures, one train must create about 10 thousand equivalent loading cycles. This is unrealistic, given the nature of the change in the stress state in the elements of spans when they are loaded with a temporary load. Hence, it follows that the indicated hypothesis of the accumulation of fatigue damage in the elements of operated span structures at a stress level below the fatigue limit of the connection under consideration cannot be accepted for assessing the durability and residual life of steel bridge structures.

Conclusions

1. The mechanical characteristics of the base metal of span structures practically do not change over 80 - 100 years of operation. The durability of a certain steel grade increases with an increase in the yield point of the metal and practically does not depend on the service life of the bridge structure at the maximum stresses in the elements of superstructures from constant and train loads up to 120 MPa or at variable stresses up to 58.5 MPa with an equivalent symmetric loading.
2. The durability of the metal of riveted elements of span structures in the area of holes from connecting rivets is lower than in the area of the same newly formed holes. This indicates the effect of its stressed state on the durability of steel, due to the concentrated effect of rivets on the metal of the elements. More research is needed to quantify this effect.
3. The results of endurance tests showed that the linear hypothesis of the accumulation of fatigue damage in the elements of the operated spans at a stress level below the fatigue limit of the connection under consideration cannot be used to assess the durability and residual life of steel bridge structures.

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