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Variation Coefficient of Metal Yield Strength in New and Long-Used Building Structures

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Abstract
Introduction. Non-destructive methods are most often used to assess the condition of the metal structure. Dangerous stress is determined by the value of the yield strength. This approach has weaknesses. This is, firstly, the probabilistic nature of the methodology (the minimum value of the indicator obtained during laboratory tests is entered into the regulatory and technical documentation). Secondly, the limitations on the number of samples should be overcome. Thirdly, the different duration of operation causes a significant difference in the mechanical characteristics of the metal, which to a certain extent complicates the long-term prediction of the condition of the structure. The presented work is designed to solve these problems within the framework of the study of new and long-operated facilities in the Rostov region. The scientific research objective is to analyze fatigue changes and determine possible degradation of the metal.
Materials and Methods. The mechanical characteristics of the material under study were reliably described by the Weibull distribution law through the shear parameter (the minimum possible value of the characteristic) and the shape parameter (magnitude dispersion). For scientific research, the indentation method based on a modified Rockwell hardness estimation method was used as part of the work. A conical indenter was embedded in the surface, then the reaction of the metal was analyzed. To implement the method, an analog-to-digital converter and a laptop were used. For correlation analysis, intermediate characteristics were taken: depth, maximum and minimum velocities, maximum and minimum acceleration of cone insertion. A correlation was established with the mechanical characteristics determined by standard tensile and hardness tests of the metal.
Results. Objects with zero and long-term operation were studied. The measurements were carried out in a warehouse, production site, stadium, bridge, Palace of Sports and on a power line support. From the group of new and used structures, one was selected for a detailed fixation of the values of yield strength. So, before the start of operation, the condition of three metal trusses of the warehouse was analyzed. It was established that the lowest value of the yield strength here was 240 MPa, the maximum was 345 MPa. On the power transmission line poles, which have been in operation for 43 years, the lowest recorded value of the yield strength was 235 MPa, the highest was 384 MPa. For each of the six structures, the minimum and average distribution of the metal yield strength values was given, and the coefficients of variation of this indicator were given. The recorded values were summarized in the form of a table. The average values for all new and used designs were calculated. Graphically presented data illustrate the growth of the coefficients of variation of the yield strength with increasing service life.
Discussion and Conclusion. A comparative analysis of the obtained values of the yield strength of building structures of approximately the same strength class suggests that the influence of operating time can both increase and decrease the studied indicator. At the same time, long-term operation is a factor that increases the average value of the coefficient of variation. To monitor the strength capabilities of the structure, it is advisable to use a non-destructive method, selectively monitoring the mechanical characteristics of the elements before and during operation.

Keywords: non-destructive testing, metal yield strength, metal of the structure in operation, metal degradation

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Научная статья

Коэффициент вариации предела текучести металла новых и долгое время эксплуатировавшихся строительных конструкций

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Аннотация

Введение. Для оценки состояния металла конструкции чаще всего применяют неразрушающие методы. Опасное напряжение определяется по значению предела текучести. У такого подхода есть слабые места. Это, во-первых, вероятностная природа методики (в нормативно-техническую документацию вносится минимальное значение показателя, полученное при лабораторных испытаниях). Во-вторых, следует преодолеть ограничения по числу образцов. В-третьих, разная длительность эксплуатации обусловливает значительную разницу механических характеристик металла, что в известной степени осложняет долгосрочное прогнозирование состояния конструкции. Представленная работа призвана решить эти задачи в рамках исследования новых и давно эксплуатируемых объектов в Ростовской области. Цель научных изысканий — анализ усталостных изменений и определение возможной деградации металла.

Материалы и методы. Механические характеристики исследуемого материала достоверно описываются законом распределения Вейбулла через параметр сдвига (минимально возможное значение характеристики) и параметр формы (рассеивание величины). Для научных изысканий в рамках работы задействовали метод индентирования, основанный на видоизмененном способе оценки твердости по Роквеллу. Конический индентор внедряется в поверхность, затем анализируется реакция металла. Для реализации метода воспользовались аналогово-цифровым преобразователем и ноутбуком. Для корреляционного анализа брали промежуточные характеристики: глубина, максимальная и минимальная скорости, максимальное и минимальное ускорение внедрения конуса. Устанавливалась корреляция с механическими характеристиками, определенными по стандартным испытаниям на растяжение и твердость металла.

Результаты исследования. Изучались объекты с нулевой и многолетней эксплуатацией. Замеры проводили на складе, производстве, стадионе, мосту, во Дворце спорта и на опоре линии электропередач. Из группы новых и отработавших сооружений выбрали по одному для подробной фиксации значений пределов текучести. Так, до начала эксплуатации проанализировали состояние трех металлических ферм склада. Установлено, что наименьше значение предела текучести здесь — 240 МПа, максимальное — 345 МПа. На опорах линии электропередач, бывших в эксплуатации 43 года, самое низкое зафиксированное значение предела текучести — 235 МПа, самое высокое — 384 МПа. Для каждого из шести сооружений приводится минимальное и среднее распределение значений предела текучести металла, даны коэффициенты вариации этого показателя. Зафиксированные значения обобщены в виде таблицы. Рассчитаны средние показатели по всем новым и отработавшим конструкциями. Графически представленные данные иллюстрируют рост коэффициентов вариации предела текучести с увеличением срока эксплуатации.

Обсуждение и заключение. Сравнительный анализ полученных значений предела текучести строительных конструкций приблизительно одного класса прочности позволяет предположить, что влияние времени эксплуатации может как увеличить, так и уменьшить исследуемый показатель. При этом длительная эксплуатация — фактор, увеличивающий среднее значение коэффициента вариации. Для мониторинга прочностных возможностей конструкции целесообразно задействовать неразрушающий метод, выборочно отслеживая механические характеристики элементов до и в процессе эксплуатации

Ключевые слова: неразрушающий контроль, предел текучести металла, металл эксплуатируемой конструкции, деградация металла

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Introduction. In diagnostics, restoration, reliability assessment or reconstruction of long-used steel structures, it becomes necessary to find out the mechanical characteristics of metal, including its fatigue indicators. For plastic materials, which include steel structures, dangerous stress is determined by the yield strength value. As it is known, it has a probabilistic nature; its minimum value obtained during laboratory tests of a limited number of samples is entered into the regulatory and technical documentation. In most cases, the metal structure condition is assessed using non-destructive testing.

Mechanical characteristics (in particular, yield strength) undergo certain changes while in service [1]. The study provides a comparative analysis of the yield strength values of the metal of one strength class in structures before operation and after decades in use. The values of the yield strength were obtained during the examination by the non-destructive indentation method.

Many sources describe metal changes during the operation of the structure. At the same time, there is no single point of view regarding the direction of such transformations. Much depends on the nature of the material and the duration of operation. Thus, in the nuclear power industry, the metal of structures almost does not change over 30-40 years of operation [2]. In [3], there is a decrease of almost 40 % in the cyclic strength of steels 20 and 45 after 15 years of storage. The authors of [4] emphasize that 40 or more years of operation of the main gas pipeline have almost no effect on the mechanical characteristics of steel. At the same time, in [5], a decrease in plasticity is recorded with a constant value of the strength limit of the gas pipeline metal after 37 years of operation. In [6], the danger of gas pipeline failures during long-term operation due to degradation processes in the metal is indicated. In [7], a decrease in impact strength after prolonged operation is described.

For 17G1C steel, in the first years of operation of the gas pipeline, there is an increase in strength with a decrease in ductility. In the period from 20 to 30 years of operation, there is a steady decrease in both strength and ductility [8]. Obviously, with significant differences in service life, we can expect a significant difference in the mechanical characteristics of the metal, which complicates the long-term prediction of the condition of the structure. The approach proposed in this article is designed to overcome this and the limitations mentioned above: the probabilistic nature of the indicator and the insufficient number of samples.

Several objects in the Rostov region with zero and long-term operation were examined. As a result, new data on the yield strength of real metal structures were collected and summarized. The objective of the presented scientific work is to analyze the changes and to assess the possible degradation of the metal.

Materials and Methods. Let us try to quantify the changes in the mechanical characteristics of the metal. To do this, we consider the same structural elements before and after long-term operation. Such monitoring is periodically carried out in relation to the metal of the main pipelines. At the same time, it is even possible to predict the residual durability of the material [9, 10]. However, it is difficult to implement such an approach for other metal structures. In this case, you can use the information obtained by the method of non-destructive testing of metal. Ensuring the correctness of such data assumes that:

– similar constructions are compared;

– the controlled elements are made of metal of the same strength class;

– the sample of processed data is quite representative.

The authors [11] claim that the strength class of steels for metal structures is determined by certain intervals of yield strength, strength and elongation. Hence, it is necessary to compare metals with mechanical characteristics that fit into these intervals. For example, for steel of strength class C-285, the yield strength is allowed in the range from 265 MPa to 285 MPa, i.e. it is determined with an error of 7.55 %.

Only non-destructive methods are suitable for the diagnosis of the existing structures. For example, acoustic emission is used for:

– finding defects in metal [12];
– monitoring of the stress state [13];
– detection of fatigue crack growth [14] in pressure vessels;
– determination of the beginning of active metal cracking [15];
– control of welded joints [16, 17].

At the same time, the issues of the optimal arrangement of devices for determining defects in structures of complex shape are solved [18].

With the help of electromagnetic control, the specified hardness of the metal is fixed [19]. In addition, methods of direct mechanical interaction with metal during indentation are used to assess:

– the residual stresses in the metal [20];
– the initial value of the yield strength [21].

Mechanical characteristics are reliably described by the three-parameter Weibull distribution law[1]:

$$F(X) \;=\; 1 - exp\,[-((X - C)/A)^B],$$

where X — value of the mechanical property; C — shear parameter that determines the minimum possible value of the characteristic; B — shape parameter by which it is possible to judge the dispersion of this property.

It is obvious that as a result of the impact of operational loads, the average, minimum values of the mechanical characteristics of the material may change. As a consequence, the standard deviation and the coefficient of variation of the values of mechanical characteristics change.

The indentation method used in the article is based on a modified Rockwell hardness estimation method. The conical indenter is shockingly (not statically) embedded into the polished test surface under the conditions:

- energy is 0.16 J;
- angle at the top is 90 °.

Then the reaction of the metal is analyzed. 10 sq. cm. of the free area of the metal [22-24] or the welded joint [25] is enough for work. To implement the method, an analog-to-digital converter (ADC) and a laptop were used. With the help of the ADC, the dependences of the speed change on the time of the introduction of the conical indenter of the mechanical part were obtained. Then the signal was programmatically processed in a laptop and the dependencies of the indenter movement and acceleration on time were obtained. Then we took the intermediate characteristics obtained from the graphs: depth, maximum and minimum speeds, maximum and minimum acceleration of the cone insertion. They became the object of correlation analysis. A correlation was established with the mechanical characteristics determined by standard tensile and hardness tests of the metal. As a result of studying metals of various strength classes, universal correlations of standard mechanical characteristics from intermediate ones were obtained and recorded. Then, when metal was indented, its standard mechanical characteristics at the point under study were almost immediately displayed on the laptop display. The instrumentation provided the total dispersion caused by the spread of properties in the metal and the measurement error. The limit values of the error of one measurement were ± 4 %. The ability to quickly obtain 10-20 values on a local section of metal eliminated this error. And with the prompt receipt of an unlimited number of measurements, a high representativeness of the sample was ensured. Before each examination, the device was calibrated:

– the yield strength was measured on samples with previously known properties obtained during standard tensile tests on the IR-200 tensile testing machine;
– then the adjustment was performed.

Results. The objective of the study was to obtain a quantitative comparative assessment of the possible degradation of metal during long-term operation. For this purpose, the values of the yield strength of steel structures with zero and long service life were fixed by the non-destructive indentation method.

Therefore, new structures were considered:

– warehouse on Lugovaya Street, 8 in Rostov-on-Don (Table 1);
– production building on 1-st Pyatiletki Street, 71 in Bataysk (Fig. 1);
– columns of the stands of the Torpedo Stadium in Taganrog (Fig. 2).

[1] GOST R 50779.27-2017 (IEC 61649.2008). *Statistical methods. Weibull distribution. Data analysis.* Electronic fund of legal and regulatory documents. URL: https://docs.cntd.ru/document/1200146523 (accessed: 19.06.2023).

Table 1

Data from the survey of metal structures of the warehouse at Lugovaya Street, 8

Yield strength values, MPa										
Truss 12				Truss 15				Truss 18		
240	265	279	298	236	263	277	305	244	270	287
240	266	280	298	237	263	277	307	244	270	287
241	266	280	298	237	263	277	307	244	270	288
241	266	280	299	237	264	277	309	248	271	289
242	267	281	299	237	264	277	309	249	272	289
243	267	281	299	237	265	277	312	249	272	289
243	268	281	300	237	265	278	313	249	273	290
244	269	282	302	239	266	278	315	249	273	290
245	269	282	303	239	266	278	317	250	273	291
247	269	282	303	241	266	278	325	252	273	292
248	270	283	304	243	266	278	329	252	273	293
248	270	283	304	243	267	279	332	253	274	294
250	271	284	306	243	267	280	339	253	274	295
250	271	284	307	245	267	280	345	254	274	295
250	271	284	307	246	268	280	351	256	274	296
251	272	284	307	247	268	281		256	275	297
251	272	285	308	247	268	281		257	275	297
251	273	285	309	249	269	282		257	275	298
251	273	286	309	250	269	282		257	277	299
253	274	286	309	250	269	283		257	277	299
253	274	287	312	252	269	284		257	277	299
254	274	287	313	252	270	284		258	277	300
254	274	288	313	252	271	284		259	278	300
254	274	288	313	252	271	285		259	278	300
255	274	289	314	253	271	285		259	278	301
255	275	289	314	253	272	285		260	279	301
256	275	290	315	255	272	286		260	279	306
256	275	290	315	256	272	286		263	279	311
257	275	290	316	256	273	287		263	280	312
258	276	291	317	256	273	287		263	281	313
258	276	291	317	256	273	287		264	282	315
258	277	291	318	256	273	288		264	282	316
258	277	291	319	257	273	289		264	282	317
258	277	291	320	257	274	289		265	283	318
258	277	291	320	258	274	289		265	283	318
259	277	292	320	259	274	290		265	284	320
260	277	292	327	259	275	290		266	284	324
260	278	293	339	259	275	291		266	284	324
260	278	293	343	260	275	293		266	284	326
261	278	294	343	260	275	295		266	284	326
261	278	294	346	260	275	295		266	285	331
262	278	295	347	260	275	297		267	285	333
262	278	295	350	261	276	297		267	285	340
262	278	296	352	261	276	300		268	285	345
264	278	296	353	262	276	301		269	286	345
264	279	296	353	262	276	302		269	286	
264	279	297		262	276	302		270	286	

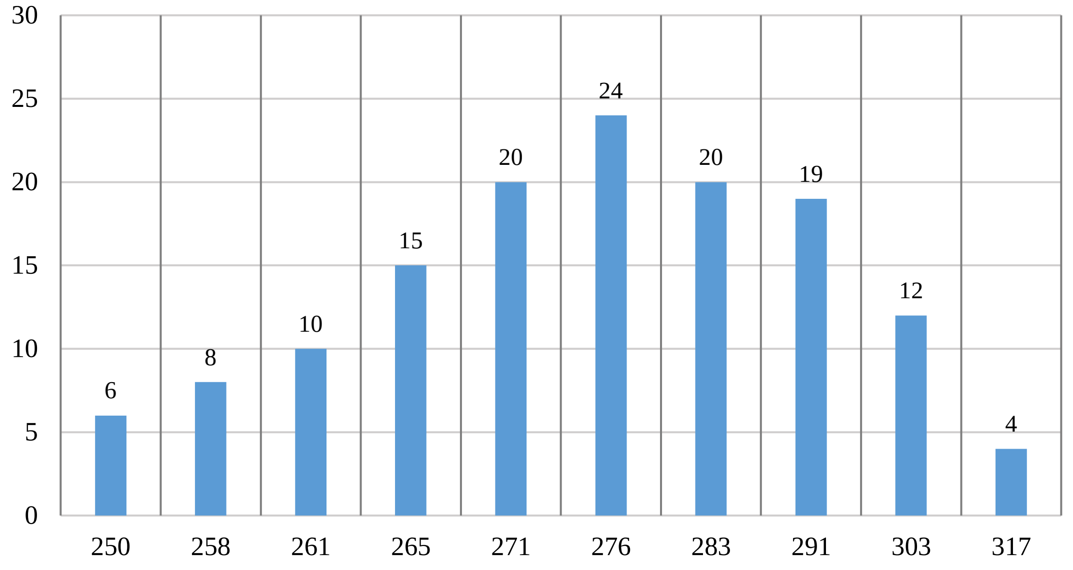

Fig. 1. Distribution of the metal structures yield strength values of the production building in Bataysk: σTmin = 246 MPa, σTcp = 277 MPa, CV = 0.054

Here and further, the sample minimum σt min, the sample average σt cp and the coefficients of variation of the yield strength CV are indicated. Ordinate is a scale of the frequency of values. The numbers above the columns are the number of measured values in a specific interval.

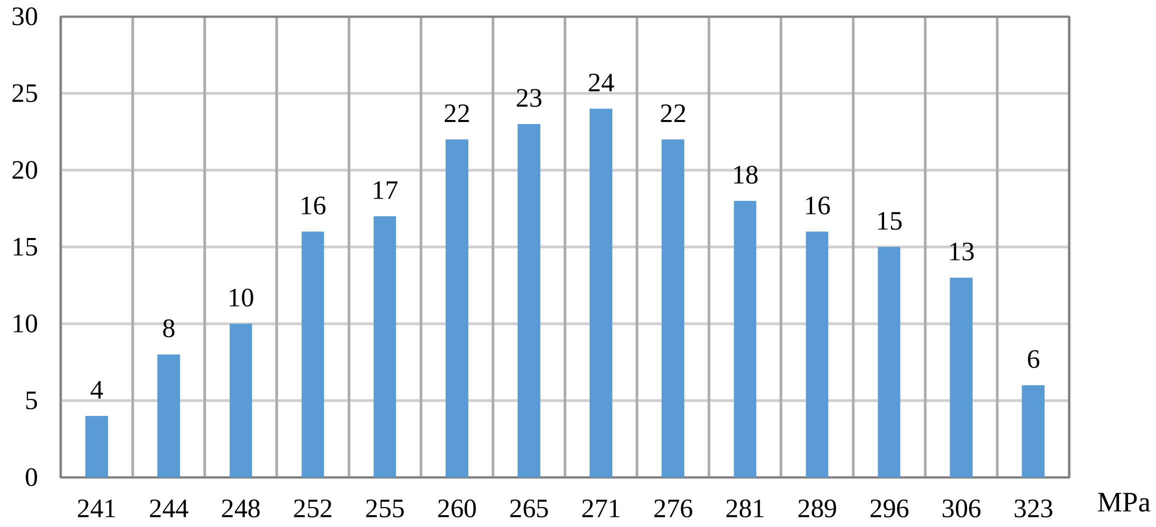

Fig. 2. Distribution of the metal yield strength values of the columns of the Torpedo Stadium in Taganrog: σTmin = 240 MPa, σTcp = 272 MPa, CV = 0.068

The metal, which had been in operation for several decades, was studied at the following objects:

– railway bridge at Likhaya station (65 years old, Fig. 3);

– the roof trusses of the Sports Palace in Rostov-on-Don (39 years old, Fig. 4);

– braces of load-bearing structures of the power transmission line poles HV line 330 "Novocherkasskaya GRES — Yuzhnaya" (43 years, Table 2).

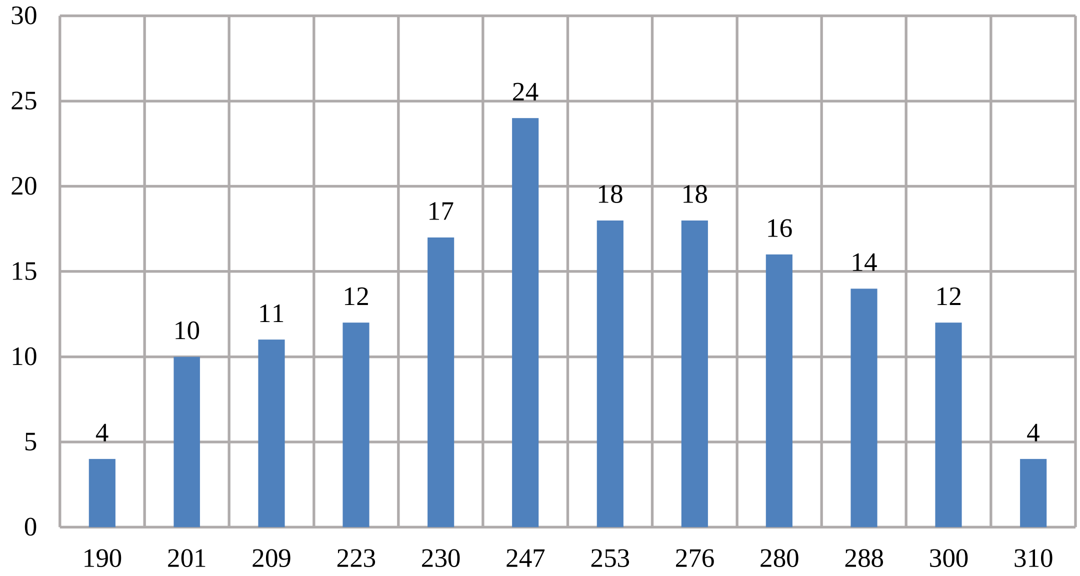

Fig. 3. Distribution of the metal structures yield strength values of the bridge at the Likhaya station: σTmin = 188, σTcp = 257, CV = 0.127

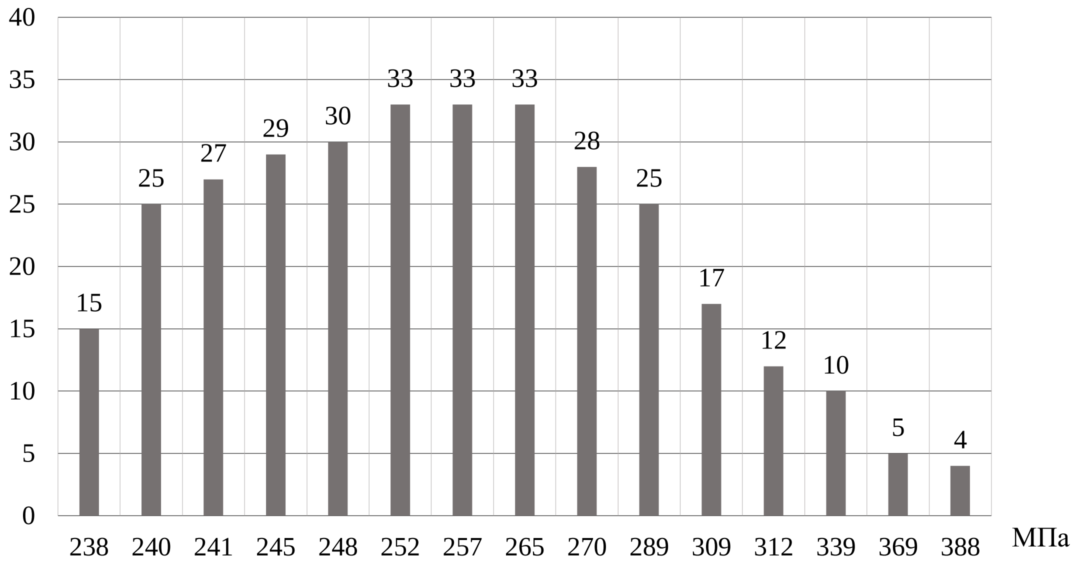

Fig 4. Distribution of the metal trusses yield strength values of the coating of the Sports Palace in Rostov-on-Don: σTmin = 238 MPa, σTcp = 263 MPa, CV = 0.11

Table 2

Examination results of power transmission line poles HV line 330

Yield strength values, MPa							
235	244	249	259	275	282	288	357
236	245	251	261	278	282	291	357
237	246	255	263	280	282	292	366
238	246	256	265	280	283	294	380
239	247	256	269	281	284	295	380
239	248	259	272	282	286	303	384

The data in Table 2 were checked for compliance with the three-parameter Weibull distribution law. It was necessary to estimate the theoretical, and not the selective minimum value of the yield strength σt min. As a result of the calculation, the theoretical value turned out to be less than the selective one by 6 MPa (229).

Let us note that the elements of the new structures were not affected by the stress-strain state, and those that were in operation for a long time were in a state of:

– compressed-bendable (upper belts of the coating trusses);

– stretched-flexed (lower belts of trusses covering);

– stretched (stretch marks).

The yield strength values obtained as a result of non-destructive testing are ranked in ascending order for better informativeness in Tables 2 and 3.

The steels of all new metal structures and HV line 330 can be attributed to the strength class C285. The metal of the bridge at the Likhaya station has an average yield strength of 8 MPa below the limit specified in [10]. The steel structures of the Sports Palace are 11 MPa higher.

The results of the comparative analysis are shown in Table 3 and Figure 5.

Table 3

Research results summary

Object	Parameters					
	Metal yield strength values, MPa				Calculation of the average coefficient of variation	
	Mean σ_T		Minimum in the sample σ_{Tmin}	Mean σ_{Tmin} for objects	Standard deviation (MPa) / CV	Average value for objects
Warehouse	276	274	236	239	23.7 / 0.085	0.069
Production building	277		246		14.5 / 0.054	
Stadium	272		240		18.5 / 0.068	
Sports Palace	263	267	256	226	28.8 / 0.11	0.123
Electric power line HV line 330	280		235		39.8 / 0.142	
Railway bridge	257		188		33,5 / 0 ,127	

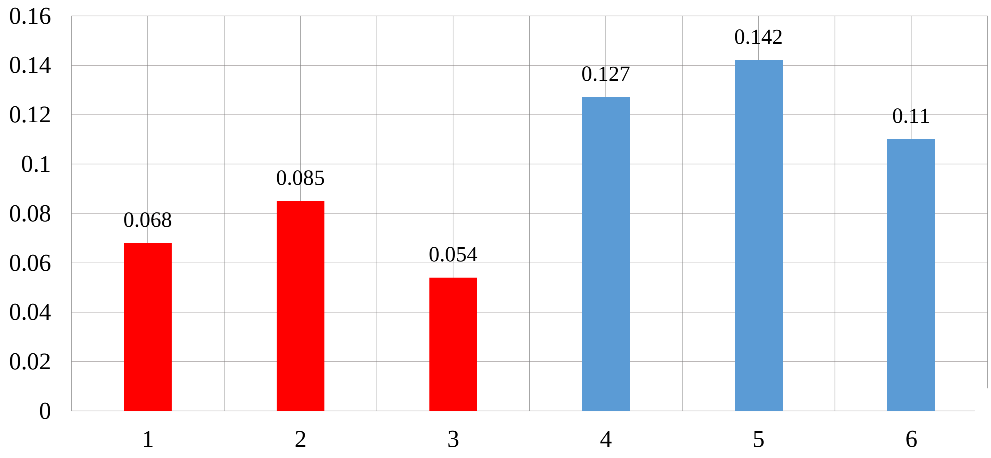

Fig. 5. Coefficients of variation of yield strength before and after long-term operation: 1 — stadium, 2 — warehouse, 3 — production building, 4 — railway bridge, 5 — electric power line HV line 330, 6 — Sports Palace

Discussion and Conclusion. Let us compare the average values of the coefficient of variation of new and long-used structures. From Table 3 it can be seen that after long-term operation, this indicator will be on average 1.78 times higher (0.123 times more than 0.069). The maximum coefficient of variation of the yield strength (0.142) was found on the power transmission line poles HV line 330 (43 years of operation). The minimum value of the yield strength (188 MPa) is for the metal of the bridge at the Likhaya station, which has been in operation for 65 years.

The possible theoretical minimum values of the yield strength decrease relative to the sample values, which can also increase the scope of the distribution and, accordingly, the coefficient of variation.

To monitor the strength capabilities (for example, for the purpose of repair or reconstruction), it is recommended to selectively monitor the mechanical characteristics of the metal structure elements by non-destructive method before and during operation.

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