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**ESTIMATION OF THE LOAD-CARRYING CAPACITY
OF THE CONSTRUCTIONS
OF THE CULTURAL HERITAGE OBJECT
«THE OLDENBURG'S COMPLEX. LOVERS BRIDGE. 1900»**

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Statement of the problem. A lot of years of uncontrolled operation of the bridge have resulted in its supporting structures to an emergency condition. For further safe operation of the bridge, structural strengthening of almost all elements is required. Since their direct strengthening is impossible without violating the original appearance, we set the task of strengthening the structures indirectly by choosing permissible schemes and limit values of loads on the span on mathematical and physical models.

Results. To solve this problem, we carried out and analyzed the results of qualitative and quantitative theoretical studies of the object of cultural heritage «The Oldenburg's complex. Lovers Bridge. 1900». We carried out an instrumental inspection of the monument, designed and tested a laboratory model of the original structure.

Conclusions. The data obtained as a result of comprehensive studies made it possible to assess the load-bearing capacity of the structures of the cultural heritage object, analyze the possibilities of loading the bridge span and make a conclusion about its further safe operation in modern conditions.

Keywords: architectural heritage, inspection of building structures, natural analogue, span structure.

Introduction. One of the architectural gems of the Voronezh region is indisputably the palace and park complex of the Oldenburgskys [6, 8] in the settlement of Ramon which is currently being restored to its former glory gradually acquiring the appearance that it had back at the turn of the 19th century. The Ramon estate, previously owned by local manufacturers Tulinov-Shele, owes its name to the family name of Evgenia Maksimilianovna of Oldenburg who received the estate that was transferred to the state treasury as a gift from her uncle, Alexander II [1].

The “Bridge of Lovers” spans over a deep log separating two Ramon hills. The bridge built at the beginning of the 20th century was operated for a long time without strength and deformation monitoring of load-bearing elements. Its safety margin was sufficient for the family members and visitors. The issue of adapting a cultural heritage object for modern use has been posed of

late [9]. The growing number of tourists would mean a rise in the load, a variety of schemes for its placement along the span and the need to increase the capacity of the bridge.

The objective of the studies described in the paper is the theoretical and experimental substantiation of the possibility of further safe operation of the cultural heritage site “The Oldenburgsky Complex. Bridge. 1900“, calculation of the span for various schemes and intensity of loading, its verification, rejection of unacceptable types of loads, development of principles for the competent organization of works aimed at preserving and adapting the object.

1. Design features of the bridge span. The supporting structures of the pedestrian bridge with the span of 9.66 m and a width of 2.67 m (Fig. 1) are made of steel and only the flooring is made of 60 mm thick pine boards.

Fig. 1. Oldenburg complex. Bridge. 19.
(Russian State Historical Archive, fund 515, signature 87, file 164, sheet 67)

According to the structural scheme, the bridge is a complex combined system comprised of three fluted beams 1 (Fig. 2) supported by inclined elements 4 on spatial arches 2 forming an arched bridge with a “ride over the top”. Besides, the resulting combined system is supported by inclined supports 3, forming a “running doe” bridge scheme with the supporting beams [4, 5, 10, 13, 17]. The main beams are braced by a system of horizontal ties 5.

Such a repeatedly statically indeterminate design scheme of the bridge enabled the designer to apply light profiles for the main load-bearing elements: beams from a brand close to the modern BT 10, and the remaining the load-bearing elements — from strip steel with the thickness of 8—10 mm [11, 14, 19, 20, 21].

All the nodal connections were designed on rivets, still preserved in some places. The supporting parts of the bridge are rigidly embedded in the brickwork of the retaining walls

of the hillsides. At the corners of the bridge there are brick pylons which are presently partially lost.

Fig. 2. Construction scheme of the bridge

Fig. 3. Structural damage span structure of the bridge:
 a) loss of rivets; b) buckling of compressed flexible elements; c) unsuccessful repair of the supporting parts of the arches (photo by A. S. Scheglov)

A visual inspection of the bridge structures is indicative of its unsatisfactory technical condition. Rivets are missing in some places, the compressed flexible elements of the bridge are bent, the supporting parts of the arches have been repeatedly altered using welding disrupting the original appearance of the elegant superstructure (Fig. 3). Some artwork of the original fencing of the crossing was broken not so long ago, which was what caused the closure of the bridge.

2. Instrumental study of the bridge span. In order to obtain data for the calculation of structures, a spectral analysis of the chemical composition of steel was performed. This survey enabled the steel grade of the span structure as well as its physical and chemical and physical and mechanical characteristics to be identified.

The bridge structures were repeatedly painted. As of now, the paint layer has been partially lost resulting in areas of corrosion (rust) of a red color with a variable thickness of up to 0.5 mm having been found during a visual inspection of the surface of the structures.

The chemical analysis of steel was performed by means of the method of chip sampling along the sample section (GOST R ISO 14284-2009). The research results are shown in Table.

Table

Chemical composition of strip steel and beams obtained by means of chip selection and steeloscopy

Material	Chemical composition, %		
	C	S	P
Steel (chip selection)	0.35	0.004	0.01
Steel (steeloscopy «SPAS—0,2»)	0.01—1	0.01—0.25	0.01—0.2
Steel (steeloscopy <i>PMI-Master</i>)	0.03	0.04	0.02
Steel 35 GOST (ГОСТ) 1050	0.32—0.40	< 0.04	< 0.035

Chemical analysis conducted by the volume (averaged for the entire sample) showed some agreement between the composition of the investigated steel and medium-carbon steel grade 35 GOST 1050.

Another qualitative analysis for impurities in the metal of the samples — steeloscopy — was performed (Fig. 4).

The samples were transported to the Laboratory of the Center for Collective Use at VSTU (emission spectrometer "SPAS-0.2") and the Laboratory of the Voronezh Mechanical Plant (optical emission spectrometer *PMI-Master*).

As the analysis was conducted on the samples cut from different elements, and the sampling was performed at different points along the cross section of the samples, there is a significant scatter of the data in terms of the amount of carbon ("SPAS-0.2") — from 1 to 0.01 %, phosphorus — from

0.01 to 0.2 %, sulfur — 0.01 to 0.25 %, there is a small amount of lead and cobalt in the alloy (these elements might have come from the paint that had been used on the bridge structures).

Fig. 4. Steeloscopy of the bridge elements (photo by A. S. Scheglov)

A spectral analysis using the PMI-Master device indicated that the chemical composition of the investigated steel is the following: C — 0.03 %; Si — 0.024 %; Mn — 0.04 %. According to the percentage of chemical elements, the steel corresponds to type E10 (10880) according to GOST (ГОСТ) 11036-75.

The fact that the data on carbon, obtained by different methods of chemical analysis is so scattered is due to the technology of manufacturing the structure by forging (on the surface, iron is carburized due to prolonged contact with smoldering charcoal). Sulfur and phosphorus in iron alloys typically form segregations (clusters), which is confirmed by the fact that there are large non-metallic inclusions. As metal refining was not in use in the early 20th century, increased amounts of impurities in different areas along the structure cross section are quite likely.

3. Analysis of the load effect in the span elements of the bridge. The objective of theoretical studies of the stress-strain was to obtain information on the actual load-bearing capacity of individual elements and the entire superstructure of the bridge as well as to identify the limiting values of the load for each of its types. As all the load-bearing structures of the bridge are visible, it is not possible to directly reinforce the elements without causing any disruption to the original appearance. The only way to "strengthen" for the further safe operation of an architectural monument is an indirect one, i.e., by limiting the current load [2, 3, 12, 15, 18].

The load in the calculations was taken according to four schemes: simulating the full loading of the entire span by a crowd of people with an intensity of 300 kg/m² (Fig. 5a); loading with

lines with an intensity of 100 kg/m^2 and a width of 1 m in a quarter (Fig. 5b) and in the middle (Fig. 5c) of the span; loading with a strip with the intensity of 100 kg/m^2 along the fence on one side of the bridge (Fig. 5d).

Fig. 5. Span loading schemes:

- a) the entire span; b) a line in a quarter of the span;
- c) in a line in the middle of the span; d) along the fence

Some calculation results obtained using the Lira software package in the form of diagrams of bending moments and longitudinal forces are shown in Fig. 6. The resulting values of the parameters of the loading effect made it possible to conclude the following:

— loading according to scheme 1 (the entire area of the bridge) with the indicated intensity is unacceptable as a lot of flexible elements of the bridge are compressed and lose stability. During the calculation, the maximum permissible loading intensity according to the first scheme was set to 180 kg/m^2 ;

— all the other loading schemes give final stresses not exceeding 145 MPa . According to the "Manual for the Design of Reinforcement of Steel Structures to SNiP II-23-81*)" in old steel elements if it is not possible to identify the design resistance, it should be taken to be equal to 170 MPa . It is thus allowed to let lines of people pass through the bridge along the width of the bridge and have them standing along the railing on one side.

Fig. 6. Loading effect in the span elements:

- a) diagram M_x according to scheme 1; b) diagram N according to scheme 1;
c) diagram M_x according to scheme 2; d) diagram N according to scheme 2

4. Verification of theoretical provisions using a laboratory model. Performing experimental studies on a full-scale object proved to be impossible due to the high costs and complexity caused by the large number of factors in play. Besides, such studies are irreproducible and inherently dangerous for the object itself, equipment, as well as researchers [2].

It has thus become necessary to simulate an actual bridge. Modeling included the design and construction of a model, the study of the properties of this model under specified conditions and influences, and the transfer of the information obtained to the modeled object.

Modeling relied on the theory of geometric and physical similarity. This means that the model M had to be similar to the natural H and that the same physical processes in the model and the object should be described by means of the same mathematical equations [7].

In our case, physical similarity was possible, while the corresponding values of the model and the natural one differed only quantitatively, but not qualitatively.

The tasks of the experimental studies on the model were as follows:

- studying of the stress-strain of the bridge model under various loads;
- identifying the experimental values of the loading effect in the span elements;
- comparing the design calculation results with the experimental data;
- studying the design principles and methods for manufacturing individual elements and parts of a steel bridge as well as methods for its construction using small-scale models.

The major dimensions of the model are 2415×690 mm as well as the cross sections and their stiffness characteristics were assigned in accordance with full geometric and physical similarity. Hence the linear scale of the simulation was

$$m_l = \frac{2415}{9660} = 0.25.$$

As a set of physical quantities determine the mechanical system is known, in order to obtain similarity conditions, dimensionless relations — similarity criteria — were compiled (denoted by the letter Π).

In order to solve the practical problems, it is more convenient to write the modeling condition in the form of so-called scale equations or similarity indicators I . The latter differ from similarity criteria in the fact that in them the physical quantities are replaced by scales. Obviously, for such phenomena, all similarity indicators are equal to one.

We had to deal with the task of testing the bridge model to identify the load-bearing capacity of the main beam of full-scale construction. The load-bearing capacity of beams of constant section (with an axis described by a circle) is given by the parameters

$$N = f(l, B, A, R^{(-)}, R^{(+)}), \quad (1)$$

where N is a longitudinal force in the arch tangent to its axis, kN; l and B are the sizes of the bridge in the plan, cm; A is the section area of the beam, cm²; $R^{(-)}$ and $R^{(+)}$ are the design compression and tension resistances, kN/cm².

The own weight of the beam in this case was not considered. Among the quantities listed in expression (1), l and $R^{(-)}$ have independent dimensions; if these quantities are used as the main ones, can be transformed into a dependence between dimensionless relations of the form with their help expression (1):

$$I_1 = \frac{m_N}{m_l^2 m_{R^{(-)}}} = 1; \quad I_2 = \frac{m_{R^{(-)}}}{m_{R^{(+)}}} = 1. \quad (2)$$

Here three groups of similarity criteria can be identified:

$$\Pi_1 = \frac{N}{A^2 R^{(-)}}; \quad \Pi_2 = \frac{B}{l} = \frac{A}{l}; \quad \Pi_3 = \frac{R^{(-)}}{R^{(+)}}. \quad (3)$$

Criterion Π_3 determines the conditions for choosing the material of the model: the ratio of its design compressive strength to tensile strength must be identical to that of the material of a full-scale object. Criterion Π_2 establishes the requirements for geometric similarity in the vertical and horizontal planes.

Similarity indicators

$$I_1 = \frac{m_N}{m_l^2 m_{R^{(-)}}} = 1; \quad I_2 = \frac{m_{R^{(-)}}}{m_{R^{(+)}}} = 1, \quad (4)$$

determine the necessary conditions for modeling.

Hereinafter, the letters m denote the scales of physical quantities, which are provided in subscripts to m . Through the course of the laboratory tests, in order to achieve the most complete similarity, it became essential to simulate an actual load. For this purpose, an additional condition was imposed on the system for the equality of the relative deflections of the beams from the action of a uniformly distributed constant load:

$$y = f\left(\frac{ql^4}{EI}\right), \quad (5)$$

where q is the intensity of a constant load, kN/cm; E is the elasticity modulus of the material, kN/cm²; I is the inertia moment of the section of the flung beam, cm⁴.

Such an equation is converted into a similarity indicator in the following way:

a) the physical quantities included in the equation are replaced by the scales of these quantities, while the exponents remain unchanged, and the numerical coefficients are made equal to one:

$$m_y = \frac{m_q m_l^4}{m_E m_I}; \quad (6)$$

b) for obtaining the similarity indicator, all the scales obtained in the previous paragraph are transferred to one part of the equation, in the other part we get a unit:

$$I_y = m_q m_l^4 m_y^{-1} m_E^{-1} m_I^{-1} = 1. \quad (7)$$

The resulting similarity indicator can be simplified under certain assumptions. Thus if the geometric scales in the direction of the x and y axes are equal ($m_x = m_y = m_l$), the indicator will take the form

$$I_y = m_q m_l^3 m_E^{-1} m_I^{-1} = 1. \quad (8)$$

Note that expression (8) does not call for the similarity of the cross-sectional shape of the beams of the model and nature, but only a certain scale of the moment of inertia m_I , i.e., the integral characteristics of the section.

In our case, i.e., full geometric similarity of sections ($m_h = m_b = m_l$), the derived scale of the moment of inertia can be used with the similarity indicator taking the form

$$I_y = m_q m_E^{-1} m_I^{-1} = 1; \quad (9)$$

considering the identity of the materials of the model and the natural $m_E^{-1} = 1$, the scale and magnitude of the load required to test the model can be obtained:

$$m_q m_l^{-1} = 1; m_q = m_l;$$

$$\frac{q_M}{q_H} = m_l = \frac{1}{4}; q_m = \frac{q_H}{4}.$$

For the laboratory tests, a model of the bridge was made on a scale of 1 : 4 (Fig. 7). All the nodal connections are made on bolts (Fig. 8).

Fig. 7. General view of the bridge model
(photo by A. S. Scheglov)

Fig. 8. Nodal connections of the bridge model elements (photo by A. S. Scheglov)

Deflections of the beams were identified at the points of attachment of combined elements (struts, spring arches) using Maksimov IIM6 deflectometers with the displacement measurement accuracy of 0.1 mm (Fig. 9a), deformations were measured with wire strain gauges (Fig. 9b) [16].

Fig. 9. Fragments of the setup of the devices:
a) deflectometers; b) strain gauges (photo by A. S. Scheglov)

The model was loaded according to four schemes shown in Fig. 4 calibrated by concentrated weights (Fig. 10).

The results of the testing of the model (Fig. 11) following their recalculation for a full-scale object yielded a good agreement with the calculation data.

The maximum discrepancies in the areas under load are within 17—25 %, which is quite acceptable and is accounted for by the compliance of the nodal fastenings of the model, the conditional loading scheme (individual loads have a larger load-bearing area on the deck), etc. In the support nodes of the bridge which are remote from the application of the load, the discrepancies are larger (up to three times), which is also accounted for by the smaller scale of the model compared to that of the load.

Fig. 10. Loading of the span structure according to the diagrams shown in Fig. 4:
a) according to scheme 2;
b) according to scheme 4 (photo by A. S. Scheglov)

Based on the results of the calculation, it was concluded that it is unacceptable to completely load the bridge span with the distributed load of 300 kg/m^2 due to overvoltage. This was confirmed by the test results. With a load corresponding to the full-scale one of about 190 kg/m^2 , the flat elements of the bridge lost their stability (Fig. 12).

Fig. 12. Loss of stability of the compressed elements of the bridge model:
a) arches at the supports; b) brace in the middle of the span (photo by A. S. Scheglov)

Conclusions. A special difference between architectural monuments and other preserved art forms is not only their historical and artistic value, but also their relevance from an applied, utilitarian point of view.

For the first time during the operation of the structures, comprehensive theoretical and experimental studies of a cultural heritage site of federal importance have been performed. The results make it possible to assess the state of the supporting structures of the bridge as unacceptable.

For further safe operation of the object and its subsequent adaptation for modern use in special sections of the project for the preservation of a cultural heritage object, without distorting the true historical appearance of the monument, it is recommended that

- the destroyed brickwork of the supporting sections of the pylons is restored;
- the damaged load-bearing elements of the steel elements of the bridge are restored;
- the brick pylons are recreated according to the surviving patterns;
- a new fence with the mandatory preservation of original elements is set up;
- the boardwalk of the span is fully replaced with the treatment of wood with antifungal drugs.

Under the condition that the load-bearing capacity of the bridge (additional layout with rivets, straightening of bent elements, strengthening of the bridge supports both in terms of metal elements and in terms of brick abutments, etc.) is restored, the following conclusions can be made:

— loading according to scheme 1 (the entire area of the bridge with the intensity of 300 kg/m^2) is unacceptable, i.e. completely filling the bridge with people (e.g., during holidays) is forbidden as a lot of flexible elements of the bridge are compressed and lose stability. The maximum intensity of continuous loading of the bridge is no more than 150 kg/m^2 (taking into account the load safety factor $\gamma_f = 1.2$). In other words, the movement of people along the span when completely filled is possible with an interval and a distance of about 1.5 m between them. Besides, taking into account the normative value of the snow load according to the modern codes of practice of 180 kg/m^2 , it is recommended that during heavy snowfalls, the span structure is immediately cleared of snow;

— all the remaining loading schemes yield the final stresses of no more than 145 MPa, which does not exceed the limit values of the stresses in the bridge elements. It is thus allowed to let lines of people pass through the bridge along the width of the bridge and have them standing along the railing.

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