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Investigation of the Stability of a Two-Span Bridge with the use of a High-Precision Laser Displacement Sensors

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Abstract. Studies of aerodynamics of bridge structures are an actual problem. Such attention is paid to the study of wind influence on bridge structures not at all by chance; a large number of cases of loss of stability of such structures are known under the influence of wind up to their complete destruction. The development of non-contact systems of measuring equipment allows solving this problem with a high level of accuracy and reliability. This article presents the results of experimental studies of wind impact on a two-span bridge using specialized measuring system based on high-precision laser displacement sensors.

1. Introduction

Nowadays bridge building's calculation of wind loads on the territory of Russian Federation is regulated by SP 35.13330.2011 Bridges and pipes.

SP 35.13330.2011 Bridges and pipes contains all basic rules of calculations of wind loads on bridge constructions including to take into account the dynamic component of the wind load, to which bridge structures are most susceptible. In a part of wind loads SP 35.13330.2011 “Bridges and pipes” contains many references on calculation methods from SP 20.13330.2016 “Loads and impacts” and using for classic buildings. Aerodynamic checking of stability consists from SP 35.13330.2011 “Bridges and pipes”: critical speed, responding for dangerous aeroelastic phenomena, gotten from aerodynamic model test results or determined by calculation must be bigger than maximum wind speed possible in bridge's area but less than 1,5 times.

In that case the information for calculation of wind loads on span structure of the bridge specified in normative documents are clearly insufficient (in SP “Loads and impacts” aerodynamic coefficients for typical cross sections are missed, data of the Strouhal number are given only for single rectangular cross sections; in SP "Bridges and pipes" in appendix N, only the coefficient of drag for the parts and elements of span structures of bridges is given, without taking into account the features of the shape of the elements).

That is why, according to point 5.48 SP "Bridges and pipes" for hanging and cable-stayed bridges, as well as steel beam bridges with spans of more than 100 m, it is necessary to check for aerodynamic stability and spatial rigidity. For structures with dynamic characteristics substantially different from those of the constructed bridges, in addition to analytical calculations, appropriate studies should be carried out on the models.

Such attention is paid to the study of wind influence on bridge structures not at all by chance; a large number of cases of loss of stability of such structures are known under the influence of wind up to their complete destruction. In our country, first, a story with the Volgograd "dancing bridge" (2010) [1, 2], the case with the Takoma bridge in the USA is widely known [3, 4].

2. Test method

The methods of numerical modeling of the wind effect on bridge structures are currently poorly developed, this is primarily due to the complexity of the mathematical solution of the connected problem, the modeling of the complex turbulent structure of the wind flow around the object under study, taking into account the dynamic similarity of this object (mass inertial and frequency similarity) [5, 6].

For this reason, we will focus on experimental research in a wind tunnel.

Currently, three main types of models and their corresponding experimental research methods are distinguished:

• Fully aeroelastic models. In this case, all the dynamic and mass-inertial characteristics of the object or its individual element are modeled. Such models are used in the testing of bridge structures at the construction stage, as well as in the testing of complete models of bridge structures. The model allows reproducing all the vibrational modes of a real object, which allows obtaining the most complete and reliable results [7, 8].

• Sectional (shut-off) models. Geometrically similar models, which are part of an elongated structure. The model is made as rigid as possible, the dynamic characteristics are reproduced by using spring suspensions in specialized stands [9, 10].

The most common method is the testing of shut-off models of span structures, since this method is optimal in terms of completeness of the results obtained, labor intensity and economic feasibility. The basic requirements for sectional models and directly to the technology of testing are well known and described in the scientific and technical literature.

Of the main features it is necessary to note the presence of a specialized test bench designed for such tests, with the presence of spring suspensions for modeling the calculated values of the natural frequencies of oscillations of the span structure and the level of its damping, as well as the seats for fastening high-precision force-moment sensors for measuring the lift, resistance and torque around the longitudinal axis [11, 12].

3. Wind speed

One of the most interesting types of bridge structures are structures with two parallel-unconnected span structures, located at a minimum distance (up to 5 meters). Such constructions include the Crimean bridge under construction, the Volgograd Bridge was designed, but only one span was built, which is one of the reasons for the occurrence of aerodynamic instability. In addition to the characteristic features of the other bridge structures of the phenomena of aerodynamic instability (vortex resonance, flutter, galloping), the appearance of a buffeting effect is possible here. Buffing is one of the types of self-oscillations, representing forced oscillations of the entire structure or its parts caused by the periodic disruption of turbulent vortices from the structural elements located in front of them when they are flowing. In this case, a breakdown of turbulent vortices from a frontal span structure located along the stream is characteristic.

The object under study is two parallel metal beam girders 150 m long (figure 1).

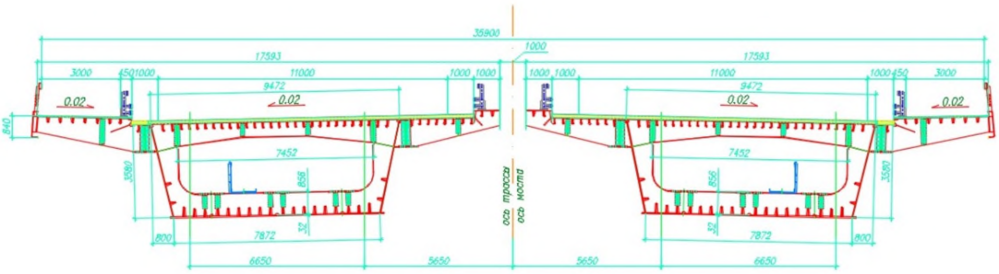

Figure 1. Cross-section of the bridge.

The canvas of the bridge is at a level of 10 m from the ground, for this altitude the standard speed value is equal to

$$U_0 = 19{,}5\, m/s \tag{1}$$

The calculated value of the speed taking into account the safety factor 1.4 will be

$$U_{\text{calc}} = U_0 \cdot \sqrt{1.4} = 23\, m/s \tag{2}$$

According to SP Bridges and pipes, the critical speed for estimating the flutter of the bridge is determined by the formula:

$$U_{\text{flut}} = 1.5 \cdot U_{\text{calc}} = 34{,}5 m/s \tag{3}$$

4. Making a layout

Taking into account the dimensions of the working part of the wind tunnel (4 mx 2.5 m), the scale of the layout of the model 1:70 was chosen as optimal from the clutter conditions. As a material for manufacturing the model, aluminum sheet is chosen to provide high accuracy of geometric similarity, lightness and high rigidity.

The model consists of two unrelated fragments of span structures of the bridge. Their length is 1714 mm, the width of each span is 254.4 mm, and the total width is 523 mm (taking into account the gap equal to 14.3 mm).

If the section model has the required mass and inertia characteristics, which are determined by the similarity laws, then the actual operation of the span structure (hereinafter - PS) will be similar and can be directly deduced from the behaviour of the PS model in the wind tunnel.

The design of the model in combination with the selected material provides not only a geometric similarity, but also the correct distribution of masses corresponding to the natural object. Thus, the geometric places of the centers of mass of the model and the natural object also correspond [6-8].

All frequency characteristics of span structures are modeled by specialized springs of the measuring stand.

Recommended values: frequency F1 = 0.542 Hz for bending vibrations and F2 = 1.003 Hz for torsional vibrations were used as reference values in this study. The level of damping of the model is measured by conducting a test and is characterized by the value of the logarithmic decrement δ. In this case, $\delta = 0.02$, which corresponds to the standard value of the logarithmic decrement for steel structures.

In accordance with the proportion in which the dimensions of the model and the bridge are related, the following table defines the scale of wind speed, dimensions and frequencies.

Table 1. Relations for the model and the real object.

Waveform	Real object	Model	Speed scale U*
Bending	0,542 Hz	9,8 Hz	3,87
Torque	1,003 Hz	18,4 Hz	3,81

5. Conducting research

When carrying out dynamic tests, the model is fixed on spring suspensions in a specialized stand (figure 2). The characteristics of spring suspensions and the corresponding flow velocity scale are determined at the design stage of the model. Movements of the model are measured using 4 optical sensors, which operate on the principle of triangulation of the laser beam. The measurement does not affect the free movement of the suspended model, bending and torsion are measured in the same way by adding or reducing the number of sensor signals.

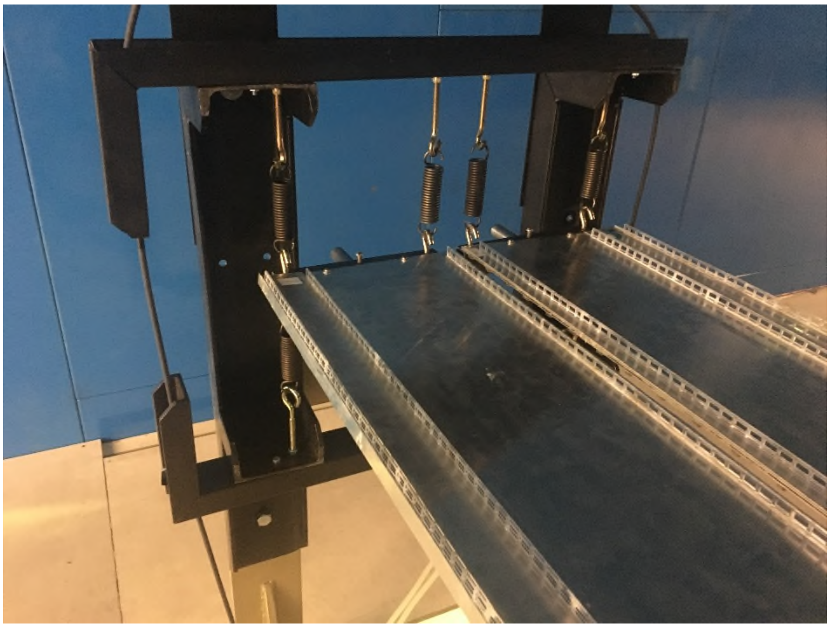

Figure 2. Model of a span structure on spring suspensions.

During the research we used laser displacement sensors LAS-T-500 with the following characteristics:

- range of displacement measurements: 100 ... 600 mm;
- minimum resolution: 0.03 mm;

The speed of the wind is measured with a Pitot tube connected to a high-sensitivity pressure sensor.

All motion sensor signals first pass a low-pass filter, then are digitized with a 16-bit analog-to-digital converter at a rate of 1000 values per second. The statistical calculation of the recorded data makes it possible to obtain mean values, rms, maximum, minimum, etc. for all measurement channels. The displacement is measured relative to the zero level at a wind speed of 0 m/s.

In figure 3 - 4 shows the results of the research, for the most unfavorable angle (+3°) from the point of view of aerodynamics. Stability measurement is presented as a plot of the PS displacement in full scale, depending on the average wind speed also in full scale. Individual graphs are performed for vertical displacement (bending vibrations) and angular displacements (torsional oscillations).

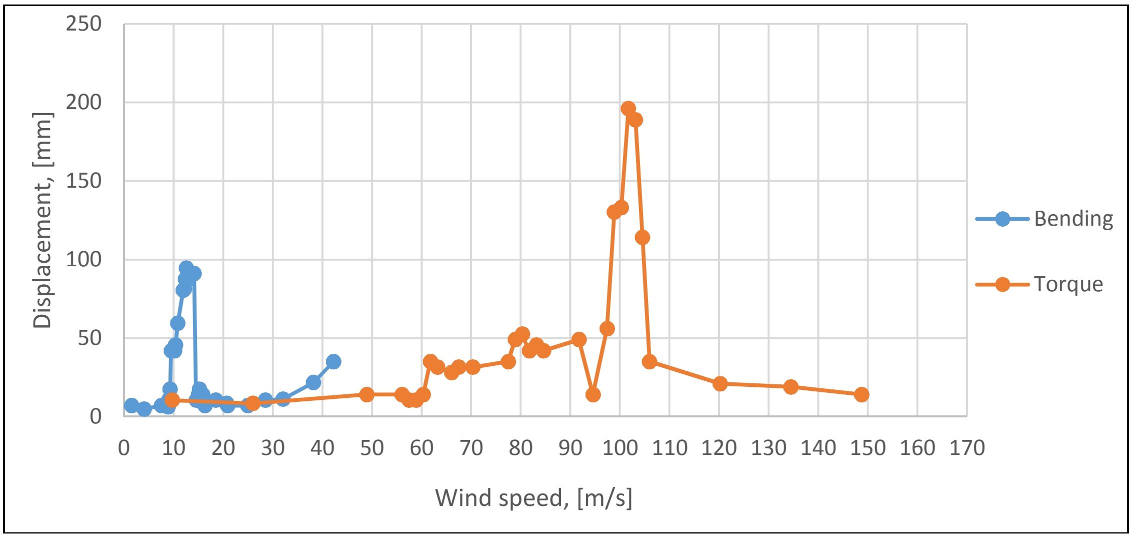

Figure 3. Dependence of the oscillation amplitude of the span structure of the bridge on wind speed, flow direction α = +3° (span on the side of the oncoming stream).

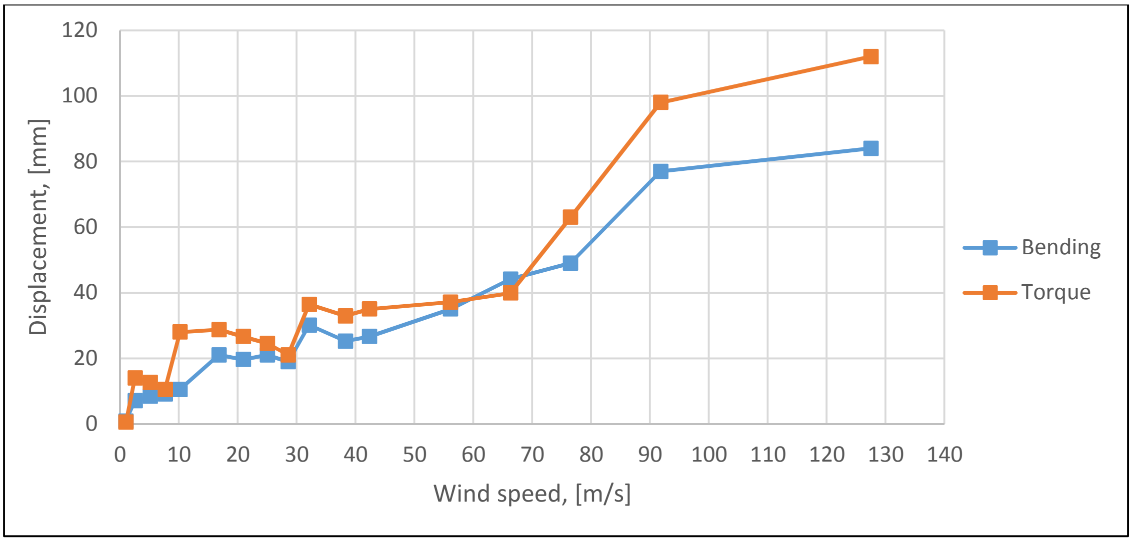

Figure 4. Dependence of the oscillation amplitude of the span structure of the bridge on wind speed, flow direction α = +3° (span located in the track).

6. Conclusions

Thus, the dynamic tests of the model showed good stability of the span structures at wind speeds below the critical flutter velocity for all flow directions. However, with the flow direction α = + 3°, the model underwent oscillations with the effect of the vortex resonance effect and the maximum amplitude of the vertical oscillations equal to the maximum permissible values: 100 mm - at a flow velocity of 11 to 15 m/s for the span located on the side of the oncoming stream, the span structure located in the track is not subject to aerodynamic instability phenomena.

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