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Stiffness Evaluation of a Metal Frame by the Method of Dynamic Tests

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Abstract – The article presents the method for assessing bending stiffness by dynamic testing using an example of the experienced metal frame. The source of forced oscillations during dynamic tests was a modal vibration exciter in the form of a mechanical oscillator with stepwise frequency control. The results of determining the natural frequencies of the frame, the frequency of forced oscillations of the exciter and logarithmic damping decrement are shown. Dynamic force and dynamic coefficient were calculated. Stiffness evaluation of the frame elements was carried out in comparison with its theoretical value specified in the finite element model. The model was compiled in the LIRA-SAPR design software 2013. For the frame elements, the curvature of a bend shape was calculated from experimental and model data. The experimental stiffness of elements on average was 8.81% less than the theoretical. The proposed approach allows realizing non-destructive testing of a bending stiffness of a structure at the measurement site.

Keywords – dynamic tests; oscillations; bending stiffness; metal structures; technical condition.

I. Introduction

Diagnostics and monitoring technical condition of construction objects during their erection and exploitation is one of the most important tasks of construction industry. There are many different methods for quality control of building structures. Destructive and non-destructive methods, as a rule, allow to determine only individual physical and mechanical characteristics of structures.

Among non-destructive methods, vibrational and seismometric methods are being intensively developed, which allow analyzing work of a structural system under load, while not bringing it to destruction. The evaluation criterion of a technical state in these methods are natural oscillation frequencies [1-5], logarithmic damping decrement [6], nonlinear distortion coefficients and amplitude modulation [7]. These criteria with different accuracy give a general integral assessment of the condition of an entire structure as a whole, but are not aimed at monitoring a single structure of the structure being operated. Actual is solution of the inverse problem of bending to calculate the bending stiffness of a test section according to dynamic test data. As a result of the solution, we obtain bending stiffness at the control site of the selected structure of the structure being operated. Comparing with the original (design) value, it is possible to estimate the residual resource and, therefore, the technical condition.

The purpose of the study is to develop a methodology for assessing stiffness of spatial metallic structures, based on solving the inverse problem of bending and conducting dynamic tests.

The main objective of the study is assessment of the actual bending stiffness of elements of the metal frame. As is known, the bending stiffness of a cross section of building structures affects deflections and movements in nodes. Testing with measurement of actual displacements at the nodes of a structure for a given static or dynamic load is low informative. The resulting movements depend significantly on nodes flexibility, mounting defects, damage during exploitation. It is possible to eliminate such factors if we calculate the curvature of a bend shape of elements of a structural system. Experiments [8] show that shape of a rod bend in a certain area depends only on the external load and stiffness of the section.

Static experiments for exploited structures are either extremely time consuming or impossible, therefore the second objective related to use of dynamic tests is relevant. Measurement of deformations with mechanical vibrations can solve this problem and will allow to evaluate the actual work of material of a structure in elastic stage.

II. Description of the Experimental Installation

The experimental setup consists of an experimental spatial metal frame, a modal vibration exciter in the form of a mechanical oscillator, and a system for recording mechanical vibrations (Fig. 1, a).

The frame is designed for testing building structures. Frame elements: girders made of I-beam 35B1, racks made of channels 120U, stiffness diaphragms made of sheet steel with a thickness of 8 mm and 12 mm.

The modal vibration exciter is an electric drill with a welded eccentric clamped in the chuck. The electric drill allows the eccentric to rotate at a constant frequency. It uses the minimum speed. The eccentric is threaded, which makes it possible to increase its mass by twisting nuts. The electric drill is fixed in a specially made welded body. Modal exciter is attached to the stiffness diaphragm between upper girders of the frame (Fig. 1, b).

The registration system consists of VS 201 (ZETlab) capacitive accelerometers and Baikal-8 recorder (P-sensor) (Fig. 1, c). The system records mechanical vibrations as a sequence of linear acceleration values in mm/s2; accelerograms are integrated to obtain linear displacement values in millimeters. The oscillation sensors were located on each rack and upper girders; fastening accelerometers was carried out using special magnets at a distance of 100 mm from each other at 3 adjacent points. Main characteristics of the registration system are shown in table 1.

TABLE I. Characteristics of the Registration System

Characteristic	Unit of measure	Value
Frequency range of accelerometers VS 201	Hz	0.1-500
Minimum value of the measured vibration acceleration	mm/sec2	20
Relative error of vibration acceleration measurement	%	5
Digitizer ADC of the recorder	unit	24
Frequency band	Hz	0-1680
Specified Sample Rate	sam/sec	1000
Specified Gain	unit	1

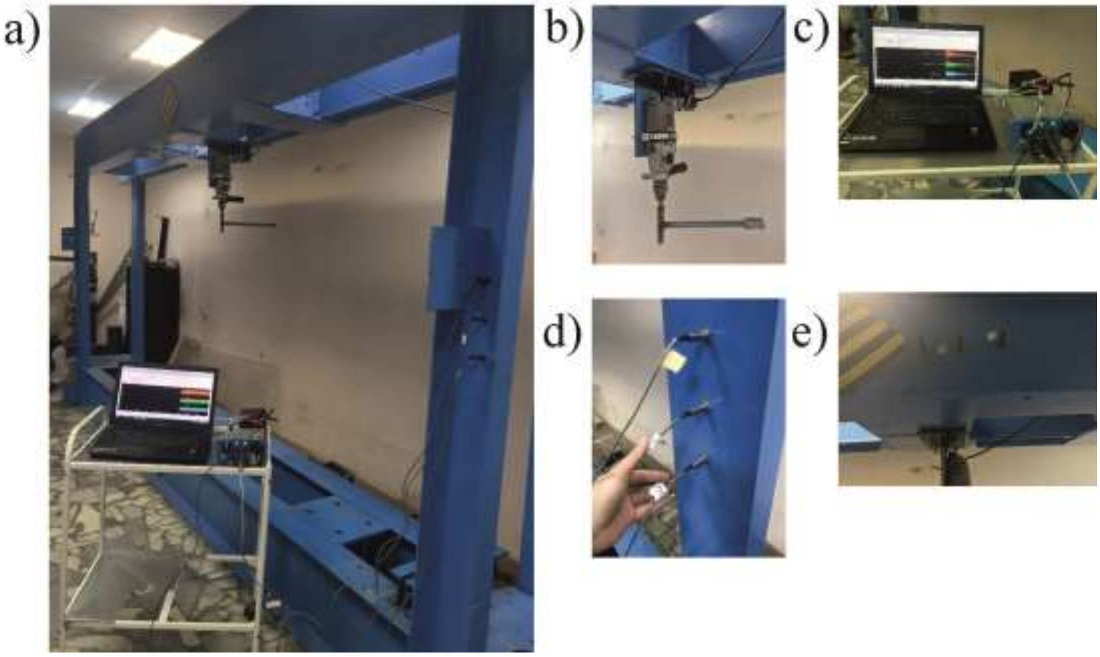

Fig 1. Experimental installation: a) general view of the frame under test; b) modal exciter; c) registration system; d) placement of vibration sensors on the frame rack; e) placement of vibration sensors on the frame girder

III. Methods of Conducting Dynamic Tests

Modelling of the test frame's structural system was carried out in the LIRA SAPR 2013 design software with the specification of cross sections and theoretical stiffness values (Fig. 2). The nodes connecting model elements are rigid; connection nodes of support lower girders are also rigid. The steel grade of all frame elements is C345 according to the data processing from hardness tester. Conditional axes were set along which vibration was recorded. The design scheme of the frame is shown in Fig. 3.

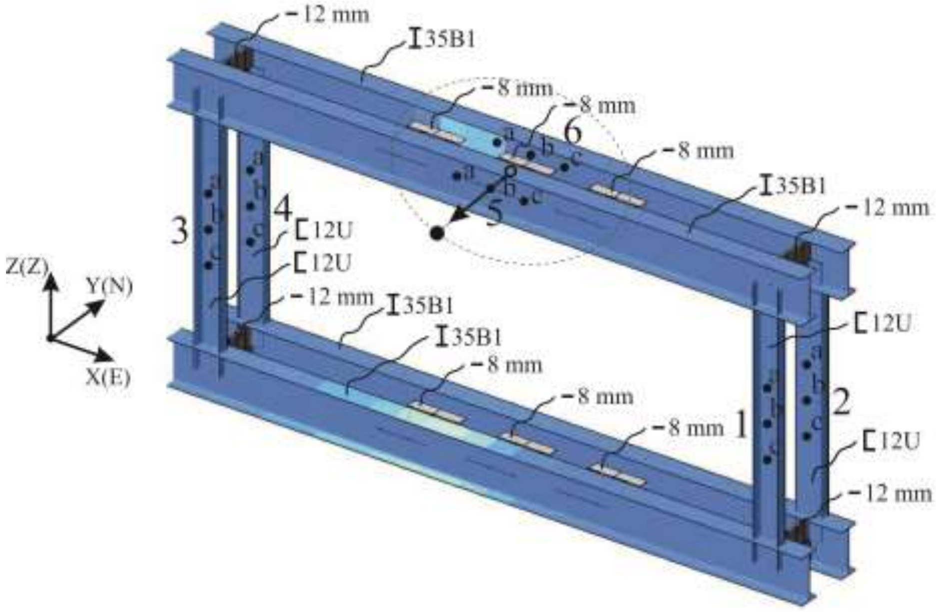

Fig 2. Model of the tested frame with sections; adopted measurement axes (left); eccentric trajectory (dashed line); a, b, c - points of vibration measurement

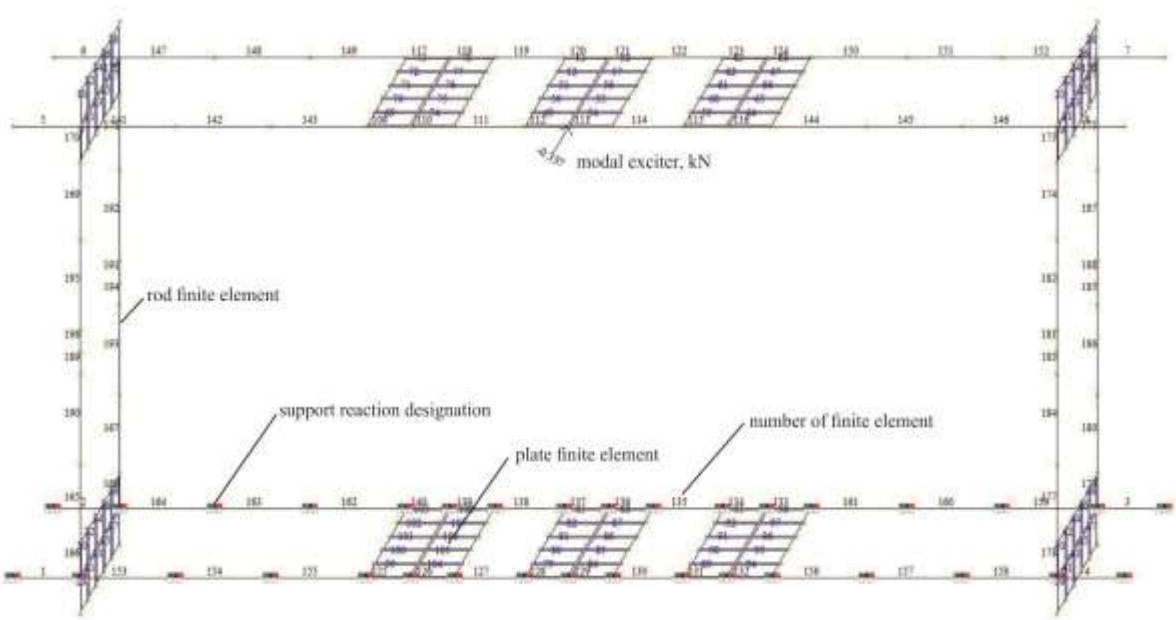

Fig 3. Frame design scheme

Dynamic test algorithm consists of 2 stages.

At stage 1, natural frequencies of the frame and logarithmic decrement of oscillations are determined. For this, the frame is unbalanced by series of impacts with a sledgehammer, which excites mechanical oscillations [9]. The vibration sensors are installed in the center of the frame on a rigidity diaphragm between the upper girders. Such an arrangement of accelerometers allows recording the most intense movement in upper points of a structure [9].

Frequencies are determined by known methods [9,10] through selection of peaks in an amplitude spectrum of vibrogram sectors containing “shocks” (Fig. 4, b). Criteria for selection of frequencies: repetition of values in all sectors, difference in value with the ratio 50 / N (N is an integer) to eliminate influence of electric machine operation.

Oscillations logarithmic decrement is defined as a natural logarithm of ratio of two adjacent critical (with zero derivative) points on a vibrogram (Fig. 5) [6]. To do this, the recording is filtered by a Butterworth bandpass filter with a width of $\Delta f = 1$

/ τ (τ is the length of a recording sector, seconds) with a central natural frequency. Root mean square is accepted as a true value.

Stage 2 of the registration includes recording forced oscillations excited by a modular vibration stand (Fig. 6). Duration of recording is 10 seconds from the time of constant frequency is reached. There are series of launches with alternate oscillations registration at each rack along the N, E axes; on the front and back girders along the axis N.

Vibrograms were processed in Windows Seismic Grafer (WSG) software.

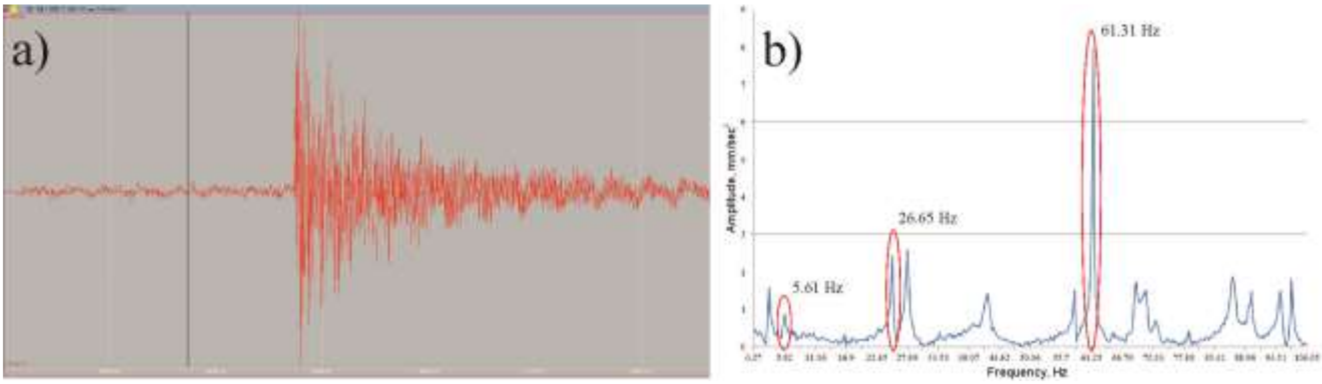

Fig 4. Vibrogram with “Shock” (a); amplitude spectrum (b)

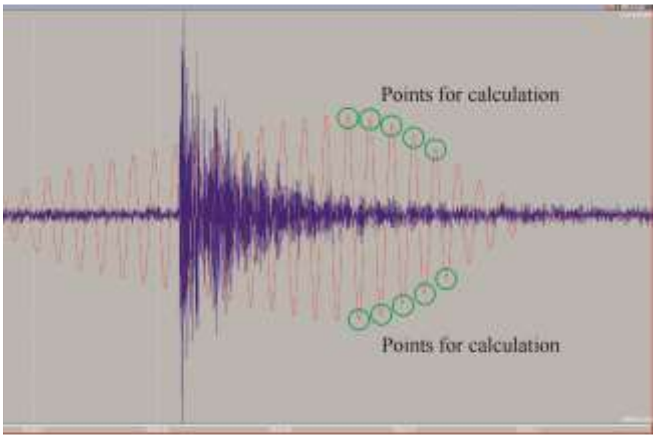

Fig 5. Initial vibrogram and filtered signal with calculated points for oscillations decrement

Fig 6. Records of modal exciter work: initial (blue) and filtered (red) vibrograms

IV. STIFFNESS EVALUATION METHOD

Evaluation of experimental bending stiffness of the frame elements is proposed to be carried out in comparison with its theoretical value, specified as ideal (design) in a finite element model [8]. To do this, the curvature of a bend rod shape of a design scheme is calculated from experimental and model data. It is assumed [8, 11] that the curvature of a bend rod shape in a control section depends on external load on a structural system and on bending stiffness within this section. By setting in a theoretical model load actually applied during tests, it can be assumed that the deviation of curvature value occurs only due to a change in the bending stiffness.

Consider two forms of curved rod axes: theoretical, constructed from design data, and actual, constructed from experimental measurements of displacements (Fig. 7, a-b) [8]. The shape of rod curved axis (elastic line) can be determined using the well-known expression:

$$\frac{1}{\rho} = \frac{M}{EJ_x}, \tag{1}$$

where $1/\rho$ is a curvature of a rod at the point; M is a bending moment from external load; EJ_x is the bending stiffness of a cross section.

In the fixed coordinate system YZ, differential equation of the rod curved axis [11]:

$$\frac{1}{\rho} = \frac{\ddot{y}}{(1+\dot{y}^2)^{3/2}}, \tag{2}$$

where $\dot{y}$ — angle of inclination θ between tangent to elastic line and axis z;

$\ddot{y} = \frac{M}{EJ_x}$ — second derivative of increment z at the point.

Consider the case of different forms of theoretical and actual rod curved axis with the same bending moment from external load. In this case, the difference in shape occurs due to a change in bending stiffness. For the theoretical shape of a curved rod, we have [8]:

$$\frac{1}{\rho_{th}} = \frac{M}{EJ_{th}};\ M = EJ_{th} \cdot 1/\rho_{th}, \tag{3}$$

where $\frac{1}{\rho_{th}}$ — curvature of theoretical bend rod shape; M — bending moment; EJ_{th} — theoretical bending stiffness of a cross section of a rod.

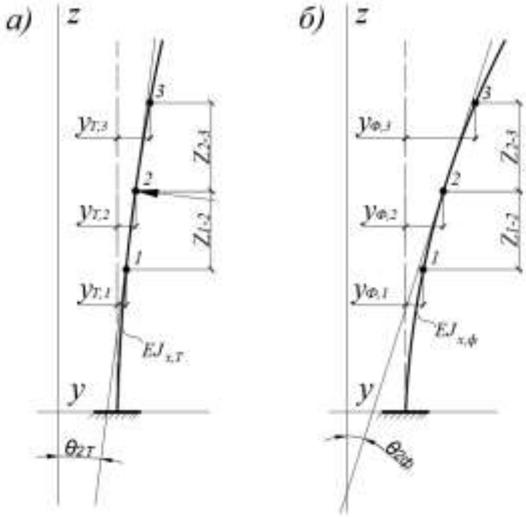

Fig 7. Forms of curved rods: a) theoretical; b) actual

For the case of actual bend rod shape [8]:

$$\frac{1}{\rho_{ac}} = \frac{M}{EJ_{ac}};\ M = EJ_{ac} \cdot 1/\rho_{ac}, \quad (4)$$

where $\frac{1}{\rho_{ac}}$ — curvature of actual bend rod shape; EJ_{ac} — actual bending stiffness of a cross section of a rod.

Equate the right parts and make a ratio of stiffnesses [8]:

$$\frac{EJ_{th}}{EJ_{ac}} = \frac{1/\rho_{ac}}{1/\rho_{th}}. \quad (5)$$

Thus, the ratio of bending stiffnesses for theoretical and actual rods is inversely proportional to the ratio of their curvatures. By calculating actual curvature of bend rod shape, it is possible to go to actual bending stiffness of a cross section in the sector under consideration.

Solution of the differential equation (2) for the considered rods according to measured displacements gives a curvature value $1/\rho$. Due to smallness of transverse displacements compared with distance between the points, the change in bending distance can be neglected. Then the first derivatives $\dot{y_1}$ and $\dot{y_2}$ at point 1 and 2 of the displacement equation are defined as [8]:

$$\dot{y_1} = \frac{y_2 - y_1}{Z_{1-2}};\ \dot{y_2} = \frac{y_3 - y_2}{Z_{3-2}}. \quad (6)$$

Second derivative at point 1 [8]:

$$\ddot{y} = \frac{\dot{y_2} - \dot{y_1}}{\frac{Z_{1-2}}{2} + \frac{Z_{2-3}}{2}} = \frac{2 \cdot \frac{y_3 - y_2}{Z_{3-2}} - 2 \cdot \frac{y_2 - y_1}{Z_{1-2}}}{Z_{1-2} + Z_{2-3}}; \quad (7)$$

Then rod curvature at the point will be equal to [8]:

$$\frac{1}{\rho} = \frac{\frac{2 \cdot \frac{y_3 - y_2}{Z_{3-2}} - 2 \cdot \frac{y_2 - y_1}{Z_{1-2}}}{Z_{1-2} + Z_{2-3}}}{(1 + (\frac{y_2 - y_1}{Z_{1-2}})^2)^{3/2}} = \frac{M}{EJ_x}, \quad (8)$$

Thus, to calculate curvature in the required sector of a structure, it is necessary to measure displacements at three points of a control sector.

To obtain displacement values, number line of accelerogram is integrated. Then, root mean square accepted as a displacement under load from modal exciter.

Load from the modal exciter is dynamic, therefore, for convenience of modelling, the load is recalculated into the appropriate static one through dynamic factor. According to the well-known formula, dynamic coefficient:

$$\beta = \frac{1}{\sqrt{(1 - \frac{p^2}{\omega^2})^2 + (\frac{\delta}{\pi})^2 (\frac{p}{\omega})^2}},$$

where ω — natural oscillations frequency; p — forced oscillation frequency; δ — logarithmic damping decrement. To calculate dynamism coefficient, it possible to take one of the natural frequencies, for which oscillations occur at the control points.

Dynamic force P_d is determined based on angular velocity ω of modal vibration exciter rotation and mass of the eccentric m_{ecc}:

$$P_д = m_{экс} \cdot a_n = m_{экс} \cdot \omega^2 \cdot R,$$

where a_n — normal acceleration during eccentric rotation; R — rotation radius.

V. Results and Discussion

Comparison of theoretical (model) and experimental natural frequencies is given in Table 2.

TABLE II. Comparison of Theoretical And Experimental Frequencies

Frequency number	Theoretical, Hz (rad/sec)	Experimental, Hz (rad/sec)
1	8.81 (55.33)	5.61 (35.23)
2	13.56 (85.16)	11.53 (72.41)
3	28.07 (176.28)	26.65 (167.36)
4	35.73 (224.38)	31.09 (195.25)
5	63.31 (397.59)	59.96 (376.55)

Frequency of forced oscillations p_{for} = 6.67 Hz (41.89 rad/sec).

Logarithmic damping decrement at natural frequency: $\delta_{5.61}$ = 0.183.

Dynamic force P_d = 141.35 N.

Dynamic factor β = 2.334.

Static force, correspondence to dynamic displacements P_{st} = 336.98 N.

Oscillations measurements were made at three points (a, b, c) of the control sectors (Fig. 2):

- sector 1 — right front rack;
- sector 2 — right back rack;
- sector 3 — left front rack;
- sector 4 — left back rack;
- sector 5 — front girder;
- sector 6 — back girder.

Bending stiffness of the experiment turned out to be consistently less than theoretical values. The average difference was 8.81%. In the control sectors there are no obvious signs of defects and damage. The significant difference can be explained by underestimation of actual strength properties of the steel compared to their standard values (the steel grade was determined by Brinell hardness) and measurement error.

The advantage of approach is ability to exclude from a stiffness calculation any displacement of a structural system outside the control sector. Thus, it is possible to obtain element-by-element residual life of a structure and evaluate its technical condition. The approach allowed creating a method of non-destructive testing of the stiffness of elements that is relevant for calibration calculations or projects to strengthen facilities in exploitation. Accuracy of the proposed method essentially depends on vibration measuring equipment used and distance between test points. Reducing a control sector and distance between oscillation sensors requires an increase in sensitivity and a decrease in a relative measurement error.

TABLE III. CALCULATION RESULTS OF BENDING STIFFNESS OF THE FRAME ELEMENTS ON CONTROL SECTORS

Sector number	Curvature, model, 1/m	Curvature, exp., 1/m	Stiffness EI, model, N· m^2	Ratio $\delta_{exp}/\delta_{mod}$	Stiffness EI, exp, N· m^2
Rright front rack					
1, N	$2.5 \cdot 10^{-7}$	$2.8 \cdot 10^{-7}$	3 131 200	1.120	**2 795 714**
1, E	$4.0 \cdot 10^{-8}$	$5.0 \cdot 10^{-8}$	232 780	1.250	**186 224**
Rright back rack					
2, N	$6.85 \cdot 10^{-7}$	$7.3 \cdot 10^{-7}$	3 131 200	1.066	**2 938 181**
2, E	$1.3 \cdot 10^{-7}$	$1.4 \cdot 10^{-7}$	232 780	1.077	**216 153**
Left front rack					
3, N	$6.9 \cdot 10^{-7}$	$7.2 \cdot 10^{-7}$	3 131 200	1.043	**3 000 733**
3, E	$1.276 \cdot 10^{-7}$	$1.37 \cdot 10^{-6}$	232 780	1.074	**216 808**
Left back rack					
4, N	$6.9 \cdot 10^{-7}$	$7.2 \cdot 10^{-7}$	3 131 200	1.043	**3 000 734**
4, E	$1.3 \cdot 10^{-7}$	$1.41 \cdot 10^{-7}$	232 780	1.085	**214 620**
Front girder					
5, N	$1.3 \cdot 10^{-6}$	$1.42 \cdot 10^{-6}$	109 098 000	1.092	**99 878 451**
Back girder					
6, N	$1.3 \cdot 10^{-6}$	$1.34 \cdot 10^{-6}$	109 098 000	1.031	**105 841 345**

VI. CONCLUSION

1. The approach to estimating stiffness of spatial metallic structures, based on dynamic tests, is proposed.

2. The considered dynamic test method allows obtaining a calibrated dynamic load and a constant frequency of forced oscillations. Accuracy of the method depends on sensitivity of instruments and distance between control points.

3. Solution of inverse problem of bending through curvature of structural system elements eliminates factors that affect resulting displacements at points in a system.

4. The difference in experimental and theoretical stiffness makes it possible to assess technical condition of both individual sectors and structure as a whole.

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