SCIENCE AND ENGINEERING

Techniques for Processing Experimental Data for Structural Health Monitoring of Bridges

Nikolay M. KVASHNIN   **Ivan S. BONDAR**   **Mikhail Ya. KVASHNIN**

Nikolay M. Kvashnin[1], Ivan S. Bondar[2], Mikhail Ya. Kvashnin[3]

[1] *ZashchitaInfoTrans, Moscow, Russia.*
[2] *International Educational Corporation, Almaty, Kazakhstan.*
[3] *Academy of Logistics and Transport, Almaty, Kazakhstan.*
✉ [2] *ivan_sergeevich_08@mail.ru.*

ABSTRACT

Reliability of transport artificial structures and transit of trains at sanctioned speed should be provided with the necessary and sufficient load-bearing capacity, strength, rigidity, and stability of engineering structures.

The objective of this work was to substantiate the possibility of using well-known methods for controlling the stress-strain state of structures using automated systems of structural health monitoring of bridge spans.

It is extremely important regarding operation of transport artificial structures designed according to the standards of the first half of the 20th century.

Under these conditions, the experimental determination of the stress-strain state of bearing structures of bridges becomes the most important component of the task of a comprehensive assessment of physical wear and tear as well as of operational reliability of the structures. Monitoring the structural health and technical condition of bridges and planning of timely measures aimed at the repair, strengthening or reconstruction of spans will extend their service life and ensure safety during operation.

Maximum permissible deflections of spans under a movable temporary vertical load have been revealed since to ensure smooth movement of vehicles it is necessary to control horizontal longitudinal and transverse displacements of the top of the bridge piers, as well as vertical settlements.

The paper suggests methods of interpreting data measured by inclinometers and electric strain gauges, tensiometers to use them in an automated system for monitoring the structural health of railway bridges. The method of strain measurement is described in detail in the proposed options for installing resistance strain gauges on structures to measure tensile-compression stresses and longitudinal forces due to a temporary vertical load.

Monitoring the technical condition of bridge structures, using the methods for measuring deflections and deformations proposed by the authors in this article, will make it possible to assess the change in bearing capacity of the structure over the entire period of operation.

The study used regulations and experience of the Russian Federation and the Republic of Kazakhstan.

Keywords: transport, infrastructure, artificial structures, bridge, bridge span, superstructure, deflection, stress, deformation, monitoring.

The text of the article originally written in Russian is published in the first part of the issue.
Текст статьи на русском языке публикуется в первой части данного выпуска.

INTRODUCTION

In accordance with the rules and regulations in force in many countries including the Russian Federation, reliability of transport artificial structures and transit of trains at sanctioned speed should be provided with the necessary and sufficient load-bearing capacity, strength, rigidity, and stability of engineering structures during the entire service life.

Long-term operation of transport artificial structures, designed according to the standards of the first half of the 20th century considering the then designed moving loads of that period, led to appearance of defects and malfunctions that affect the conditions of train running on bridge and speed of rolling stock. Therefore, the experimental determination of the stress-strain state of bearing structures of bridges becomes the most important component of the problem of a comprehensive assessment of physical wear and tear and operational reliability of the structure. Monitoring the structural health of bridges built according to the old design standards, and timely measures for repair, strengthening or reconstruction of spans, will extend their service life and ensure safety during operation.

The set of rules for design of bridge structures has stipulated the maximum permissible deflections of superstructures due to a movable temporary vertical load to ensure smooth movement of vehicles. During monitoring, it is necessary to control horizontal longitudinal and transverse displacements of the top of the bridge piers, as well as their vertical settlement.

Now, there are several methods for monitoring the technical conditions and structural health of superstructure of large and unique railway bridges.

The *objective* of this work was to substantiate the possibility of using well-known methods of control of the stress-strain state of structures using automated systems of structural health monitoring of bridge spans.

THE APPLIED METHODS

When developing automated monitoring systems, it is recommended to use electronic deflectometers (flexometers), inclinometers with an electrical output signal. To measure deformations (stresses), electrical resistance strain gauges (tensiometers) are used: strain gauge sensors or strain gauge resistors. The deflections of bridge spans under load are determined using geodetic instruments, mechanical and electronic deflectometers with wire connection, as well as inclinometers: tilt and angular displacement sensors. Currently, though being relatively new devices, inclinometers allowing the conversion of a tilt angle in a proportional output electrical signal have been adopted for widespread industrial use [1, p. 20].
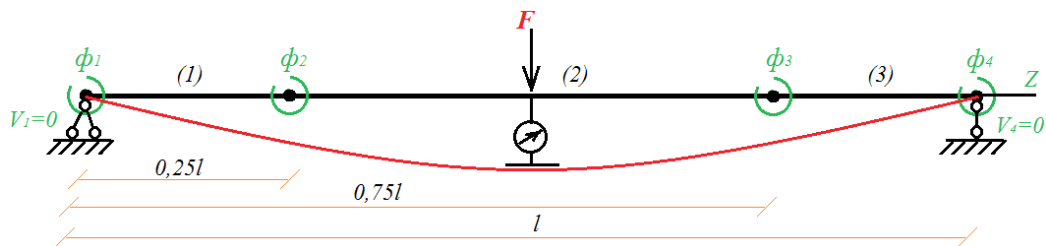
The use of mechanical and electronic deflectometers with wire connection in testing flyovers can significantly increase the accuracy and simplify the process of measuring deflections in comparison with geodetic measurements. However, the need to have a rigid connection with the ground, the so-called reference point, relative to which the measurements take place, makes it impossible to use them to measure the deflections of bridge spans located over water obstacles [1, p. 20].

In recent years, with long-term measurements (monitoring) of deflections of bridge spans, it became possible to use inclinometers: tilt and angular displacements sensors.

The analysis of the stress state of elements of full-scale structures, as a rule, is performed based on measuring deformations on the surfaces of the studied objects. Among the experimental methods for measuring deformations (mechanical, acoustic, electrical, optical, moiré, mesh methods, etc.), most researchers prefer measurements using electrical resistance strain gauges: strain gauge sensors or strain gauge resistors [2, p. 13]. The strain gauge best meets the cost-effectiveness criterion, having the optimal combination of characteristics traditionally used for evaluating a strain gauge system. These characteristics are:

• Calibration constant of the sensor, which must have temperature and time stability.

• The error in measuring deformations, which should not exceed 1 µm/m in the range of deformations ± 5 % (± 50 000 µm/m).

• Length and width of the sensor that must be small enough to adequately measure the deformation at the point.

• Inertia of the sensor, which should be small enough to register high-frequency dynamic processes.

• Linearity of the sensor response within the entire measurement range.

• Efficiency of the sensor and associated devices.

• Minimum requirements for skills of the operating personnel required to install equipment and perform measurements [2, p. 13].

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Pic. 1. Design scheme of the superstructure (Report on research and development work on the topic «Creation of a monitoring system for potentially dangerous objects of railway transport using GLONASS/GPS/GALILEO systems». Moscow, FSUE ZashchitaInfoTrans, 2020, 154 p.).

Currently, strain gauges are used in more than 80 % of stress state studies conducted in the industry of the USA, Japan, and other developed countries. Besides, strain gauges are widely used as sensitive elements of sensors designed to measure forces, moments and pressure [2, p. 13].

RESULTS
Methodology for Interpreting Data Measured by Inclinometers

It is known that the maximum deflection of the bridge span structure (in the middle of the span) should not exceed the limiting value:

$$f_{max} \leq f_u, \tag{1}$$

wher f_u is limiting deflection value, regulated, e.g. in the Russian Federation and the Republic of Kazakhstan, respectively, by clauses 5.43 of SP 35.13330.2011[1] and 5.6.1 of SP RK 3.03-112-2013[2].

According to the requirements of clause 5.43 of SP 35.13330.2011 and clause 5.6.1 of SP RK 3.03–112–2013, vertical elastic deflections of span structures, calculated under the action of a movable temporary vertical load, for railway bridges should not exceed the values:

$$\frac{1}{800-1,25 \cdot l} \cdot l, \text{ but not more than } \frac{1}{600} \cdot l, \tag{2}$$

where l is calculated span length, m.

For the span structure of a railway bridge $l = 126$ m, the limiting deflection value, regulated

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[1] SP [here and further SP means Code of practice for construction industry of the Russian Federation] 35.13330.2011. Bridges and pipes. Updated edition of SNiP [here and further SNiP means Construction standards and rules] 2.05.03-84. [Electronic resource]: https://docs.cntd.ru/document/1200084849. Last accessed 24.05.2021.

[2] SP RK [here and further SP RK means Code of practice for construction industry of the Republic of Kazakhstan] 3.03-112-2013. Bridges and pipes. Astana, 2013. [Electronic resource]: https://www.egfntd.kz/upload/NTD/%D0%A1%D0%9F%20%D0%A0%D0%9A/113%20%D0%A1%D0%9F%20%D0%A0%D0%9A%203.03-112-2013.pdf. Last accessed 24.05.2021.

by clause 5.43 SP 35.13330.2011 and clause 5.6.1 SP RK 3.03-112-2013, is:

$$\frac{1}{800-1,25 \cdot 126} \cdot 126 = 0,196 \text{ m.}$$

When determining the deflection of structures by the direct method, by measuring the vertical displacement in the central part of the span, it is necessary to fix the displacement sensor on a fixed support. In most cases, especially with long spans, this is not possible. In practice, indirect methods of measuring the quantities are mainly used, according to which the deflections of the structure are calculated. In this case, the deflection is proposed to be determined indirectly, through the measured values of the angles of rotation of the structural nodes.

In case of determining the deflection by an indirect method, through the measured values of the angles of inclination of the structural nodes, the unknown function of deflection along the length of the beam can be determined using the methods of strength of materials [2, p. 28], considering the differential dependence of the deflection on the angle of rotation:

$$dv/dz = \phi(z). \tag{3}$$

The proposed method for determining deflections through the angles of inclination is applicable for beam elements with one span and two rocking piers (Pic. 1).

The deflections of the beam over the piers equal to zero are taken as the boundary conditions. The method gives the greatest convergence in the case when the points of measurement of the angles of rotation are made at a distance from the piers equal to 25 % of the span length. The disadvantages of this method refer to the constraints imposed on the sensors' attachment points for measuring the angles of rotation. The advantages refer to a high degree of convergence (deviation is no more than 5 %) and the use of a small number of sensors for measuring the

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Table 1

No.	Z_2, mm	Z_3, mm	α_{IN2}, arc. sec.	α_{IN2}, arc sec.	φ_2, radian	φ_3, radian	$v\left(\dfrac{l}{2}\right)$, mm
1	31500	94500	-18	-18	$-8{,}722{\cdot}10^{-5}$	$-8{,}722{\cdot}10^{-5}$	-3,14
2	31500	94500	-360	-360	$-1{,}744{\cdot}10^{-3}$	$-1{,}744{\cdot}10^{-3}$	-62,80
3	31500	94500	-1152	-1152	$-5{,}582{\cdot}10^{-3}$	$-5{,}582{\cdot}10^{-3}$	-200,96
4	31500	94500	-1152	-1152	$-5{,}582{\cdot}10^{-3}$	$-5{,}582{\cdot}10^{-3}$	-25,63
5	31500	94500	-1152	-1152	$-5{,}582{\cdot}10^{-3}$	$-5{,}582{\cdot}10^{-3}$	-197,23
6	31500	94500	-1152	-1152	$-5{,}582{\cdot}10^{-3}$	$-5{,}582{\cdot}10^{-3}$	200,96
7	31500	94500	-1152	-1152	$-4{,}846{\cdot}10^{-3}$	$-5{,}330{\cdot}10^{-3}$	162,45

angles of rotation. In this method, it is assumed that it is sufficient to describe the deflection function of a beam element with one span by a third-order polynomial with four unknown coefficients:

$$v(z) = az_3 + bz_2 + cz + d. \qquad (4)$$

From the differential dependence (3), the function of the angles of rotation is determined by an expression of the form:

$$\phi(z) = 3az_3 + 2bz + c. \qquad (5)$$

Finding the values of unknown coefficients requires solving a system of four equations:

$$\begin{cases} v(z_1) = az_1^3 + bz_1^2 + cz_1 + d \\ v(z_4) = az_4^3 + bz_4^2 + cz_4 + d \\ \varphi_2 = \varphi(z_2) = 3az_2^2 + 2bz_2 + c \\ \varphi_3 = \varphi(z_3) = 3az_3^2 + 2bz_3 + c. \end{cases} \qquad (6)$$

After solving the system of equations (6), the values of the beam deflections are calculated according to the dependence (4).

Solving the system of equations (6), to find the unknown coefficients, we use the boundary conditions (Pic. 1) $v(z_1) = 0$; $v(z_4) = 0$; $z_1 = 0$; $z_4 = l$ (we will not use the boundary conditions $z_2 = \frac{1}{4}{\cdot}l$ and $z_3 = \frac{3}{4}{\cdot}l$ since some deviations are possible when installing the sensors measuring angles of rotation). Solving the system of equations (6) under the given boundary conditions, we obtain the following expressions for the unknown coefficients:

$$d = 0;$$

$$a = \frac{\phi_3(2z_2 - l) + \phi_2(l + 2z_3)}{3(z_3^2 - z_2^2)(2z_2 - l) + 2(l^2 - 3z_2^2)(z_3 + z_2)};$$

$$b = \frac{\left[\begin{array}{c}\phi_3(2z_2 - l) + \\ +\phi_2(l + 2z_3)\end{array}\right](l^2 - 3z_2^2)}{\left[\begin{array}{c}3(z_3^2 - z_2^2)(2z_2 - l) + \\ +2(l^2 - 3z_2^2)(z_3 + z_2)\end{array}\right](2z_2 - l)} + \frac{\phi_2}{(2z_2 - l)};$$

$$c = \frac{\phi_2(4z_2 - l)}{(2z_2 - l)} - \frac{\left[\begin{array}{c}\phi_3(2z_2 - l) + \\ +\phi_2(l + 2z_3)\end{array}\right](l^2 - 3z_2^2)}{\left[\begin{array}{c}3(z_3^2 - z_2^2)(2z_2 - l) + \\ +2(l^2 - 3z_2^2)(z_3 + z_2)\end{array}\right](2z_2 - l)}. \qquad (7)$$

Substituting the values of the coefficients (7) into the formula (4), we obtain the following expression for determining the deflection in the middle of the span:

$$v\left(\frac{l}{2}\right) = \frac{l^2(18z_2^2 - 14z_2l + l^2)\left[\begin{array}{c}\phi_3(2z_2 - l) + \\ +\phi_2(l + 2z_3)\end{array}\right]}{24(z_3^2 - z_2^2)(2z_2 - l)^2 + {} \atop {} + 16(l^2 - 3z_2^2)(z_3 + z_2)(2z_2 - l)} + {} \atop {} + \frac{\phi_2 l(16z_2 - 3l)}{4(2z_2 - l)}. \qquad (8)$$

For the considered span of a railway bridge, $l = 126$ m. The values z_2 and z_3 are measured after installing tilt angle meters on the span structure. It should also be noted that the values of the angles of rotation ϕ in radians measured by inclinometers are substituted into expression (8):

$$\phi = \frac{\pi\alpha_{IN}}{3600 \cdot 180}, \qquad (9)$$

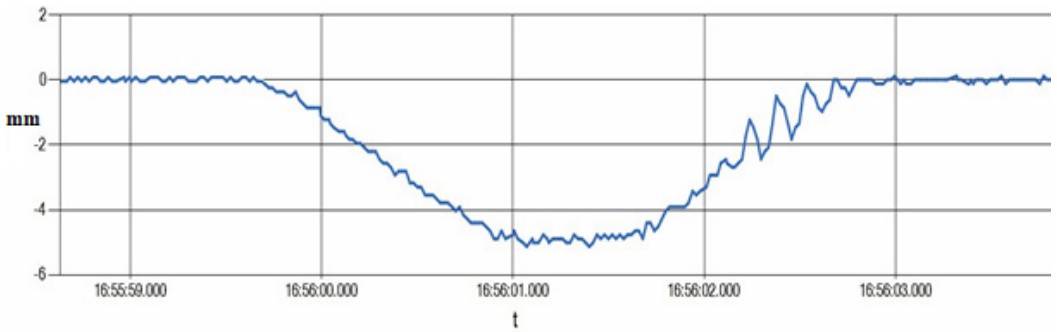where α_{IN} is the value of the angle of rotation according to the readings of the IN-D3ts-3600 inclinometer in arc seconds.

Some values of the deflections calculated by expression (8) at various values of the initial and measured parameters are given in Table 1.

When conducting trial operation of the monitoring system, it is advisable to provide software with a module for visualising the measured data [3–7]. It is advisable to visualise the data obtained from inclinometers by constructing diagrams of the deflections of the bridge span during rolling stock movement. An example of a deflection diagram for a split span is shown in Pic. 2 [8–10].

It is recommended to evaluate the performance of the structures according to the actually measured values of the deflection at each passage of rolling stock over the bridge in accordance with Appendix V to SP

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Pic. 2. An example of a deflection diagram of a split span structure (Technical report. Inspection and testing of the railway overpass according to the scheme 16,5+23,6+16,5 m over the road of the II category at the 56th km (kilometric point PK9 + 50) of Kulsary–Tengiz railway line. Almaty, JSC KazATK n.a. M. Tynyshpaev, 2018, p. 126).

Table 2

Threshold values of controlled deflections in terms of «norm/alarm/accident»

No.	Indicator name	f_{max}, mm	$K = f_{max}/f_u$
1	Threshold value of the boundary «norm/alarm»	0…137,2	0…0,7
2	Threshold value of the boundary «alarm/accident»	137,2…196	0,7…1

* The given numerical values are refined according to the results of accumulation and statistical analysis of the values of deflections of the middle of the span, measured during the monitoring process, arising under the actually planned moving load.

79.13330.2012[3] and with Appendix G to SP RK 3.03-113-2014[4] using a coefficient calculated by the formula:

$$K = f_{max}/f_u, \qquad (10)$$

where f_{max} is maximum deflection value in the middle of the span determined according to expression (8);

f_u is limiting deflection value in conformity with the clause 5.43 SP 35.13330.2011 and the clause 5.6.1 SP RK 3.03-112-2013.

The values of the coefficient K, greater than unity, calculated from the values of maximum deflections, unambiguously indicate a significant difference in operation of the structure elements as compared to the assumptions adopted in the calculations (the elements of the structure do not work within elastic limits). In these cases, it is urgent to develop measures to ensure reliable operation of elements. For the period of trial operation, it is recommended to accept the threshold values of controlled deflections, in terms of «norm/alarm/accident», given in Table 2.

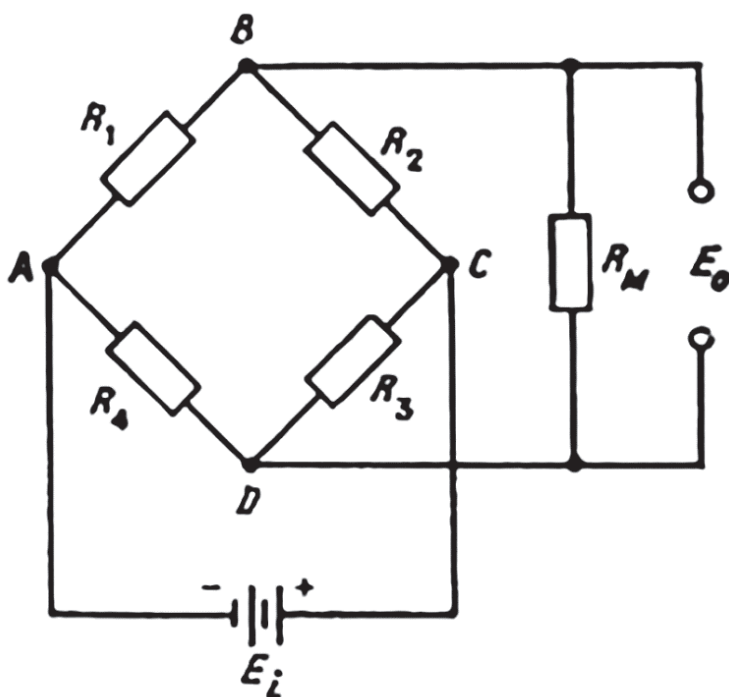**Method for Interpreting Data Measured by Strain Gauges**

According to the requirements of clauses 6.9, 6.18 SP 79.13330.2012[3] and clauses 7.2.6, 7.3.6 SP RK 3.03-113-2014[4], internal forces (forces, moments) in structural parts and elements of railway bridges under a movable temporary vertical load during dynamic tests (when rolling stock passes), should not exceed the internal forces arising under the temporary vertical load, determined by the calculation method according to the current regulatory documents.

To determine the forces arising from a moving temporary vertical load during the passage of a rolling stock, it is necessary to measure deformations, and then, using the law of deformation for the material in question, to calculate stresses and forces. Deformations are measured by strain gauges, which are easy to attach to the surface of the structure's material.

Strain gauges (tensiometers) are complex electrical devices that allow strain measurement. Since the measurement range of resistance of the strain gauge is very small, it reaches for a 120 Ohm sensor about 0,00024 Ohm for a strain of 1 μm/m. This means that a deformation of 1000 μm/m will change the

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[3] SP 79.13330.2012. Bridges and pipes. Inspection and testing rules. Updated edition of SNiP 3.06.07-86. [Electronic resource]: https://docs.cntd.ru/document/1200095530. Last accessed 24.05.2021.

[4] SP RK 3.03-113-2014. Bridges and pipes. Inspection and testing rules. Astana, 2014. [Electronic resource]: https://www.egfntd.kz/upload/NTD/%D0%A1%D0%9F%20%D0%A0%D0%9A/114%20%D0%A1%D0%9F%20%D0%A0%D0%9A%203.03-113-2014+.pdf. Last accessed 24.05.2021.

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Pic. 3. Wheatstone bridge with constant voltage source [2, p. 38].

resistance of 120 Ohm sensor to 0,240 Ohm. To measure such small voltages, bridge circuits are most often used in measuring instruments. These circuits operate from a direct current or voltage source.

Pic. 3 shows a circuit of operation of a measuring bridge powered from a DC voltage source (Wheatstone bridge). Wheatstone Bridge is depicted by an equilateral rhombus, where the sides are branches, and the tops are the nodes of the bridge. A voltage source and four resistor strain gauges (R_1, R_2, R_3, R_4) form a bridge. R_M resistor allows electrical current to flow through the bridge without wasting energy.

The output voltage E_0 of the measuring bridge (the voltage difference between points B and D) is determined by the relation [3, p. 211]:

$$E_0 = \frac{(R_1 R_3 - R_2 R_4)}{(R_1 + R_2)(R_3 + R_4)} \cdot Ei. \qquad (11)$$

From equation (11) it follows that $E0 = 0$, if the condition is satisfied:

$R_1 R_3 = R_2 R_4$ or $R_1/R_2 = R_4/R_3$. $\qquad$ (12)

If equality (12) is observed, the bridge is called balanced. This means that the small out-of-balance voltage caused by the change in resistance is measured relative to zero or near zero. This signal can easily be amplified to a high level for subsequent recording.

The output voltage E_0 occurs when the resistance of the resistors R_1, R_2, R_3, R_4 changes by the values ΔR_1, ΔR_2, ΔR_3, ΔR_4. Such changes in resistance arise, for example, due to deformation or thermal expansion of strain gauges. In accordance with equation (11), the change in the output voltage E_0 caused by these small changes in resistance is [2, p. 42]:

$$E_0 = \frac{r}{(1+r)^2} \cdot \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right)(1-\eta) \cdot Ei, \; (13)$$

where η is term characterising the error (nonlinearity of the bridge), described by the ratio:

$$\eta = \frac{1}{\left(\dfrac{1+(1+r)}{\dfrac{\Delta R_1}{R_1} + \dfrac{\Delta R_4}{R_4} + r\left(\dfrac{\Delta R_2}{R_2} + \dfrac{\Delta R_3}{R_3} \right)} \right)}, \qquad (14)$$

where r is the ratio of resistances R_2/R_1 or R_3/R_4.

From expressions (13) and (14), the properties of the measuring bridge that are important for practical applications follow:

• Deformations acting on the strain gauges of the opposite branches of the bridge are summed up within the limits of measuring bridge.

• Deformations acting on the strain gauges of adjacent bridge branches are subtracted within the limits of measuring bridge.

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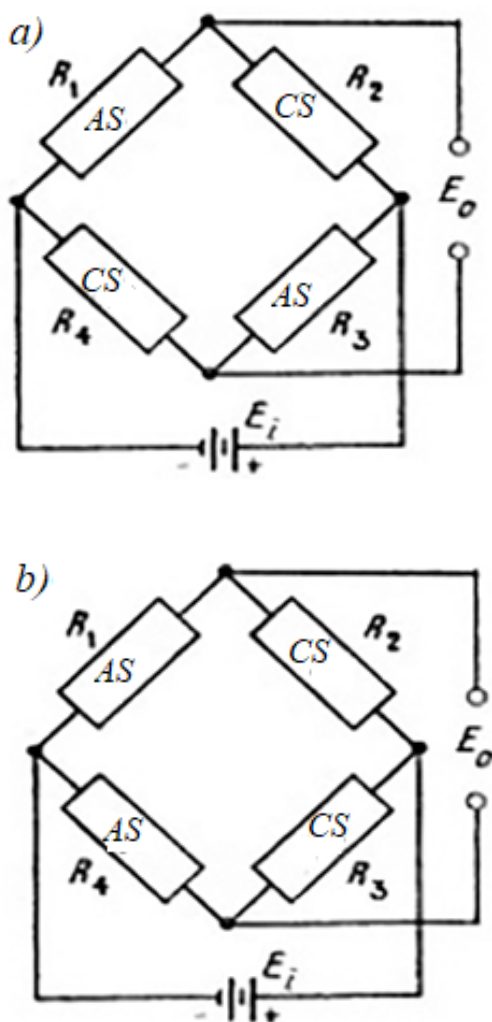
Pic. 4. Options for including strain gauges in a full bridge when measuring deformations [2, p. 56]. AS – active sensor; CS – compensation sensor. a) to measure tensile-compressive deformations εN; b) to measure bending deformations εM.

• The bridge error η (nonlinearity) is proportional to the algebraic sum of all deformations perceived by the strain gauges within the limits of measuring bridge [2, p. 43].

For the simple case there is the equality of all four resistances (i.e., $r = 1$). As it is easy to see from expressions (13) and (14), the term corresponding to the error η turns into zero when ΔR_1 and ΔR_4 are equal in magnitude and opposite in sign when $\Delta R_2 = \Delta R_3 = 0$, and when ΔR_2 and ΔR_3 are equal in magnitude and are opposite in sign with $\Delta R_1 = \Delta R_4 = 0$. This result is important since the nonlinear operation of the bridge is not essential when two active sensors are used simultaneously in opposite branches ΔR_1 and ΔR_4

or ΔR_2 and ΔR_3. With one active sensor, nonlinearity leads to an error of 1 % if $\Delta R_1/R_1$ is less than 0,02 (a value usually corresponding to a strain of 10000 μm/m) [2, p. 43].

The influence of the load resistor R_M on the value of the ideal output voltage E_0 can be determined by analysing the resistance of the load connected in series with the bridge. The result is expressed as:

$$E_{01} = \frac{R_M}{R_M + R_B} \cdot E_0 = \frac{E_0}{\left(1 + \dfrac{R_B}{R_M}\right)}, \qquad (15)$$

where E_{01} is actual output voltage and the value is the effective bridge resistance [2, p. 43]:

$$R_B = \frac{R_1 R_2}{(R_1 + R_2)} + \frac{R_3 R_4}{(R_3 + R_4)}. \qquad (16)$$

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As follows from equation (16), if all the bridge branches have the same resistance R_g then $R_B = R_g$. Thus, with $R_M > 100R_g$ for a bridge with the same branches, the error does not exceed 1 %. This condition is easily implemented with most commercial measuring instruments, since R_M usually exceeds $100R_g$. It should be noted that the considered effect of the load can be considered by the appropriate calibration technique [2, p. 43].

Pic. 4 shows the circuits of integration of strain gauges in the measuring bridge according to the full-bridge circuit when using two active and compensation sensors in the four branches of the bridge used in the practice of measuring the deformations of structures. In this case, active sensors are glued to the structure in a diametrically opposite way (the same is done with compensation sensors).

Option *a* is used to measure tensile-compressive deformations ε_N arising in the structure of the main beam of the bridge span during the passage of rolling stock. Option *b* is used to determine sensitivity of the measuring system to bending deformations ε_M. It should be noted that from the point of view of sensitivity of the output voltage arising on the measuring bridge during deformation, options *a* and *b* are absolutely equivalent to each other, which follows from the analysis of expression (13).

In these options for including strain gauges in the measuring bridge, strain gauges are used that have equal resistance (from the same batch), so that *r* is equal to 1. The main advantages of this version of the bridge are temperature compensation, linearity (if all ΔR increments are the same in magnitude) and the possibility of designing measuring circuits devoid of undesirable sensitivity to bending or axial loading.

Since a strain gauge circuit is used to measure very small changes in resistance occurring in a bridge sensor, then any influence that can change the resistance of various components of the bridge is significant because it affects the magnitude of the output voltage. The main components of the measuring circuit are strain gauges (strain resistors), connecting wires and connection points (both soldered and terminal connections). Although solder connections, contacts and terminals can introduce significant errors, these problems can be solved by minimising them and using appropriate calibration techniques.

The more complex problem is associated with electrical noise. Electrical noise induced on the measuring bridge and signal lines by magnetic fields from the power supply line might be a serious problem. The magnitude of the voltage induced in the signal transmission lines by the current flowing in the power supply line is proportional to the area of the loop formed by the lines and is inversely proportional to the distances between the lines. The following precautions should be taken to reduce noise [2, p. 66]:

1. To reduce the area of the loop, only twisted conductors should be used. In twisted connection wires, the induced noise is practically the same in both wires, which leads to a significant reduction in common-mode noise. The length of the conductors should be kept to a minimum by placing the differential amplifier close to the strain gauge bridge. Excessively long conductors should not be coiled to avoid induction [2, p. 66].

2. Only shielded cables should be used. The shield must be connected to the negative pole of the power supply. In this case, there are no currents flowing from the «ground», and the shield keeps the potential close to zero. The power supply must not be connected to ground of the device to avoid ground loops in the power supply [2, p. 66].

3. It is necessary to use only differential amplifiers with effective general noise suppression [2, p. 66].

A strain measurement system typically includes one or more strain gauges, bridge resistors, allowing to build a bridge circuit, bridge ballast resistors, one or more power sources, an amplifier, and a recording device. Each of the listed elements contributes to the resulting sensitivity; therefore, calibration of the entire system is preferable of compared with an expensive calibration of each of its components [2, p. 66].

The readings of the recording device d_r are associated with the deformation in each branch of the bridge by the following relationship [2, p. 66]:
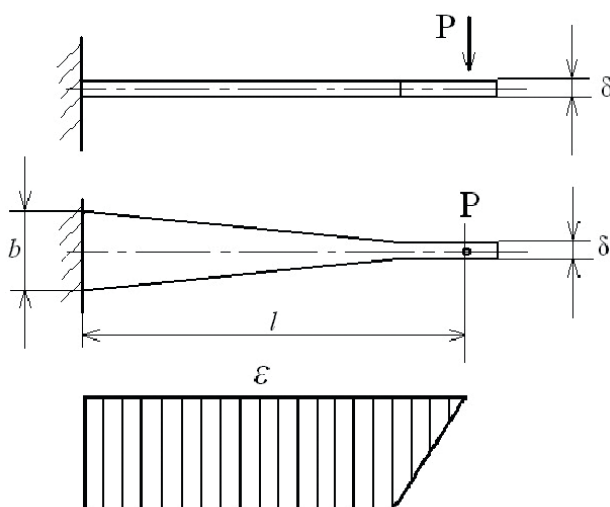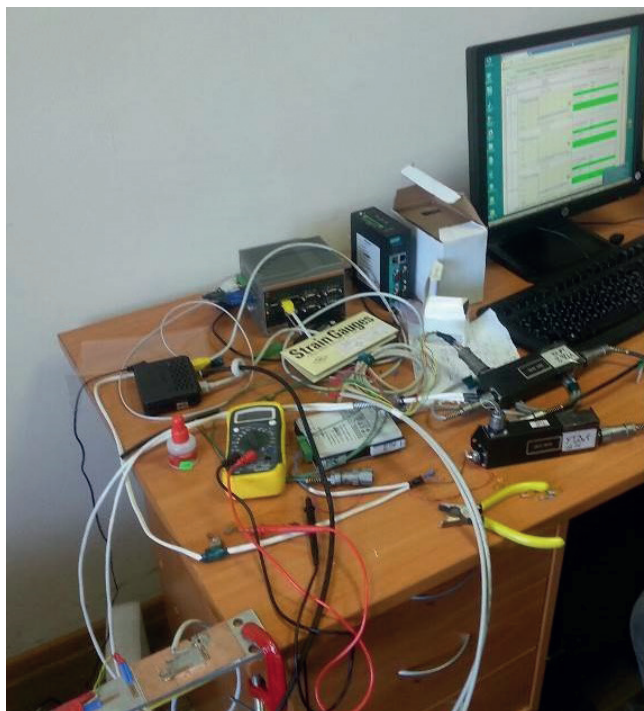
$$d_r = \frac{rGEi(1-\eta)S_g}{(1+r)^2}(\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4) = S_R \varepsilon_B, \qquad (17)$$

where *r* is ratio of resistances R_2/R_1 or R_3/R_4;

G –coefficient of amplification of the amplifier and the recording device;

E_i – bridge supply voltage;

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Pic. 5. Scheme of a calibrated cantilever beam of equal resistance[5].

η – non-linear term;

S_g – coefficient of tension-sensitivity, or of sensitivity of the strain resistor (the parameter of the strain resistor, provided for in its specifications, reflecting the behaviour of the «grid/base/glue»

[5] Report on research and development work on the topic «Creation of a monitoring system for potentially dangerous objects of railway transport using GLONASS/GPS/GALILEO systems». Moscow, FSUE ZashchitaInfoTrans, 2020, 154 p.
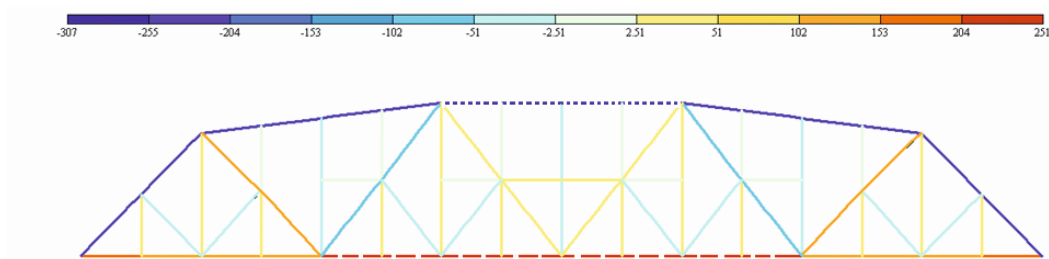
system), is defined as the ratio of the increment of resistance of the glued strain gauge to the relative deformation of the sample measured in the direction of the axis of the strain gauge:

$$S_g = \frac{\Delta R / R}{\Delta l / l} = \frac{\Delta R / R}{\varepsilon}, \qquad (18)$$

where ε_i is deformation in the i-th branch of the bridge;

S_R – overall sensitivity of the system;

Pic. 6. Mosaic chart of longitudinal forces in the elements of the main truss of the span structure (SpS 2) under the permamanent load N_{per} (own weight of the structure and the weight of bridge floor according to reference guide). Blue colour (dot line) at the top (-307 – -255) indicates compressive internal forces, red colour (dash line) at the bottom (204–251) indicates tensile forces[5] (in t).
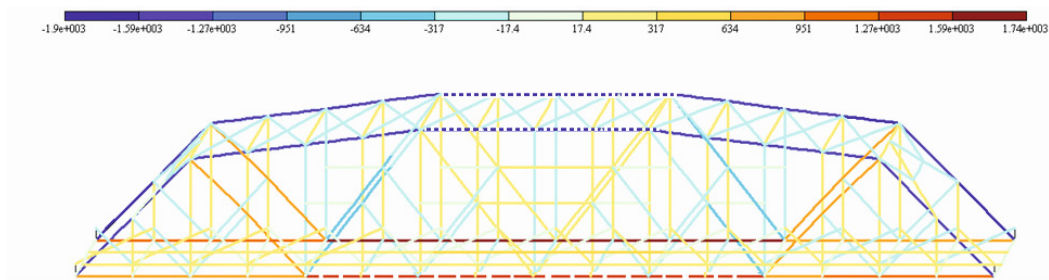
Pic. 7. Mosaic chart of longitudinal forces in the elements of bridge span structures under the joint effect of permanent load and temporary vertical load ($N_v + N_{per}$). Blue colour (dot line) at the top (-307 – -255) indicates compressive internal forces, red colour (dash line) at the bottom (204–251) indicates tensile forces[5] (in t).

ε_B – efficient deformation measured by the device.

Efficient deformation ε_B is expressed as follows:

$$\varepsilon_B = \varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4 = n_\varepsilon, \qquad (19)$$

where $n = 1$ for one active sensor (AS), $n = 2$ for two AS.

The sensitivity of the measuring system of the prototyped monitoring system was determined by the mechanical calibration method. The calibration was carried out as follows: the previously known deformation values were fed to the input of the measuring system, and the system's responses to these influences were recorded at the output.

The source of the reference deformation was a calibrated cantilever beam of equal resistance (Pic. 5). Strain gauges were glued on the beam of equal resistance according to the scheme b of Pic. 4, connecting wires (length, type etc.) corresponded to those used in the measurements of bridge structures [11–12].

The value of deformation of the beam of equal resistance was determined according to the formula:

$$\varepsilon = \frac{6Pl}{E\delta^2 b}, \qquad (20)$$

where P is concentrated force acting on the end of the console;

l – distance from the point of application of the force P to any arbitrary cross-section;

b – width of the section at the point of rigid fixing of the beam;

δ – thickness of the beam;

E – modulus of elasticity of the material of the beam.

The strain gauge sensitivity coefficient for the used batch of strain gauges ($S_g = 2,09$) was set in the basic settings of the recording device. After connecting the bridge circuit to the module, the measuring bridge was balanced, the indicator of the device was set to zero position. The load was created by weights that were applied to a weight-lifting suspension put on the free end of the beam. The weights were selected so that the reference deformations calculated by formula (20) were 100, 200, 500, 1000 μm/m. The proportionality coefficient (scale division of the measuring device) for the calibrated measuring system was determined by the formula:

$$K_{Pr} = \varepsilon cal/dr. \qquad (21)$$

During the calibration, it was found that the system has a linear coefficient of total sensitivity

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Threshold values of controlled deflections in terms of «norm/alarm/accident»

No.	Indicator name	N, t	$K = N_{max}/N_{tens}$
1	Threshold value of the boundary «norm/alarm»	0…1190	0…0,8
2	Threshold value of the boundary «alarm/accident»	1190…1489	0,7…1

* The given numerical values are refined according to the results of accumulation and statistical analysis of the values of longitudinal forces measured in the process of monitoring, arising under the actually planned moving load.

in the range of deformation measurements from 100 to 1000 μm/m, in this range the proportionality coefficient $K_{Pr} = 2000$.

When the deformation control system is launched at the tested object, the installed measuring bridges are balanced for each module used (by setting the instrument indicators to zero position). The calculation of the magnitude of the measured tensile-compression deformations ε_N arising during passage of rolling stock under the temporary vertical load during the monitoring process is carried out according to the following formula:

$$\varepsilon_N = d_r \cdot K_{Pr} = 2000 \, dr, \, [\varepsilon_N] = [\mu mk/m]. \quad (22)$$

The calculation of tensile-compressive stresses σN, arising during passage of rolling stock under the temporary vertical load is carried out using the values of deformations εN measured in this way according to Hooke's law:

$$\sigma_N = \frac{\varepsilon_N E}{1000000}, \, [\sigma_N] = [MPa], \quad (23)$$

where E – Young's modulus of the material of the structure $[E] = [MPa]$.

The elastic modulus when calculating stresses by formula (23) is taken equal to 206000 MPa, according to the data specified in table 8.13 of SP 35.13330.2011[1].

The calculation of the longitudinal forces N arising in the structural elements of the main beam of the lower chord of the truss of the span structure of the bridge during passage of rolling stock under the temporary vertical load is carried out according to the calculated values of stresses σ_N according to the formula:

$$N = 100 \cdot \sigma_N \cdot S, \, [N] = [m], \quad (24)$$

where S is cross-sectional area of the structure, m².

According to the available design documentation, the cross-sectional area of the structure of the main beam of the lower chord of the truss of the span structure of the railway bridge on the controlled section is equal to:

$$S = \frac{4 \cdot 140 \cdot 12 \cdot 2 + 2 \cdot 1000 \cdot 14 + 2 \cdot 1000 \cdot 12}{1000000} = 0,065 \left[m^2 \right].$$

It is recommended to evaluate the performance of the structures of the bridge according to the measured values of deformations, tensile-compression stresses and longitudinal forces arising in the structure during passage of rolling stock in accordance with Appendix B of SP 79.13330.2012[3], using a coefficient calculated by the formula:

$$K = \frac{\varepsilon_{N \max}}{\varepsilon_{tens}} = \frac{\sigma_{N \max}}{\sigma_{tens}} \frac{N_{\max}}{N_{tens}}, \quad (25)$$

where ε_{Nmax}, σ_{Nmax}, N_{max} are, respectively, the maximum measured values of deformations, tensile-compression stresses, and longitudinal forces under the temporary vertical load;

ε_{tens}, σ_{tens}, N_{tens} are, respectively, the values of deformations, tensile-compression stresses, and longitudinal forces under a temporary vertical load, determined by calculation according to the current regulatory documents.

The values of K coefficient, greater than unity, indicate a loss of bearing capacity due to high corrosive wear of the structure (a decrease in the working area of the beam section). In this case, it is urgent to develop measures to ensure reliable operation and reinforcement of structural elements.

According to the results of calculating the longitudinal forces in the elements of the main truss of the bridge span structure [13, p. 124], performed by the finite element method, the maximum design forces from the action of a temporary vertical load in the controlled region are:

$$N_{tens} = (N_v + N_{Per}) - Nv = 1740 – 251 = 1489 \text{ m}.$$

The calculation was carried out by mathematical modelling according to the existing design documentation for the structure, without considering the actual wear of the structures, with tolerances in accordance with SP 35.13330.2011 and SP RK 3.03-112-2013. From the mosaic chart of longitudinal forces (Pics. 6, 7), it can be seen that, according to the calculation, the lower chord of the truss suffers the greatest permanent and temporary tensile forces.

The recommended threshold values for the period of trial operation in terms of «norm/alarm/accident» for the measured longitudinal forces

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under the temporary vertical load are suggested in Table 3.

BRIEF CONCLUSION

The authors analysed the experimental and design data of more than 30 bridges and flyovers [14−17]. The methods proposed in this work are recommended to be used in development of automated systems for monitoring the structural health and technical condition of span structures of large and unique railway bridges.

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Information about the authors:
Kvashnin, Nikolay M., *Ph.D. (Eng), Chief Project Engineer of Science and Technological Centre of Development Directorate of FSUE ZashchitaInfoTrans, Moscow, Russia, kvashnin_nm@mail.ru.*

Bondar, Ivan S., *Ph.D. (Eng), Ph.D. in transport construction, Associate Professor at the Faculty of General Construction of International Educational Corporation (KazGASA), Almaty, Kazakhstan, ivan_sergeevich_08@mail.ru.*

Kvashnin, Mikhail Ya., *Ph.D. (Eng), Associate Professor, Associate Professor at the Department of Transport Construction of Academy of Logistics and Transport (ALiT), Almaty, Kazakhstan, kvashnin_mj55@mail.ru.*

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