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EXPERIMENTAL DETERMINATION OF VALUES OF THE NOSING FORCES IN A STEEL RAILWAY BRIDGE

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Keywords: *steel bridge, longitudinal girders, "in situ" measurement, deformations, nosing forces*

ABSTRACT

During the movement of the railway vehicles in the longitudinal direction, are realized chaotic movements in the transverse direction, also. The last lead to the appearance of forces that are transverse to the axis of the road. The actual normative documents for the design of railway bridges indicate different values of these forces, and the differences between them are not small. At the same time, the literature on the topic does not indicate how these forces are defined. Therefore, a group of researchers from the University of Architecture, Civil Engineering and Geodesy (UACEG) has decided through a series of field measurements to determine the real values of the nosing forces. For this purpose was selected a steel bridge with an open road structure, suitable for the research. The longitudinal beams are the structural elements of the bridge, closest to the place of application of the nosing force. Therefore, sensors are placed on their flanges, through which the authors have determined the values of the nosing forces of actually crossing passenger and freight trains.

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1. Introduction

Due to the imperfections of the track and the railway vehicles, when the trains run in the longitudinal direction, there are also movements in a transverse direction. As a result, the wheel flanges, which do not allow the trains to derail, touching the rail's head, cause forces transverse to the road axis. According to the "Standard for the design of road and railway bridges and culverts" by 1990 [1], the transverse horizontal force in railway bridges has a characteristic value Q_{sk} = 60 kN. According to the standards BS 5400-2:2006 [2] and BDS EN1991-2: 2006 [3], the nosing force has a value Q_{sk} = 100 kN. When taking into account the coefficient for classified loads α = 1,21, specified in BDS EN 1991-2: 2006/NA:2015 [4], the characteristic value increases to Q_{sk} = 121 kN. The difference in Q_{sk} in the above-written standards [1] and [3,4] is more than twice. The question arises as to which of the above normative documents prescribes more realistic values. In an attempt to find an answer to this question, in 2020 a research team from the University of Architecture, Civil Engineering and Geodesy (UACEG) performed field measurements, on the basis of which the corresponding equivalent values of the transverse horizontal forces, generated by real railway trains, crossing a steel bridge with an open road structure, were calculated [5]. From the calculations, made on selected six passenger and two freight trains, the following results were obtained [6]:

a) for passenger trains, the total nosing forces, applied to both longitudinal beams, do not exceed 14 kN;

b) for freight trains, the maximum values of the total transverse forces are of the order of 18÷30 kN.

On one hand, it is evident that under the specific conditions of the conducted experiment, the values of the nosing forces are significantly smaller than the prescriptions of the regulations [1-4]. On the other hand, the accounted forces, determined in 2020, are based on a relatively small number of passing trains. Therefore, to increase the representativeness of the study and refine the results, the research team conducted additional field tests in 2021 on the steel bridge described above.

2. Type and basic data of the investigated steel riveted bridge

The bridge, on which the values of the equivalent horizontal nosing forces have been experimentally determined, is located on km. км. 18^{+985} on a Second main railway line Sofia-Mezdra-Varna, between stations "Romcha" and "Vlado Trichkov". It is a double-span steel railway bridge, see fig. 1, located above the river Iskar. In each span are placed two truss main girders, simply supported on the lower chord by fixed and linearly movable steel bearings. The deck is classic, "open type" (rails and wooden sleepers step directly on the longitudinal beams), see fig.2. Pin-joined longitudinal and transverse beams, having approximately similar heights, construct it. The transverse beams of the road structure are supported in the nodes along the upper chord of the truss main girders. Railway sleepers are wooden and are fastened by bolts or angle sections to the upper flange of longitudinal beams.

Fig. 1. General view of the researched steel bridge on км. 18[+985]

Fig. 2. “Open type” deck structure

The cross-sections of the longitudinal beams and the numbering of the strain sensors, placed on them, are shown in fig. 3.

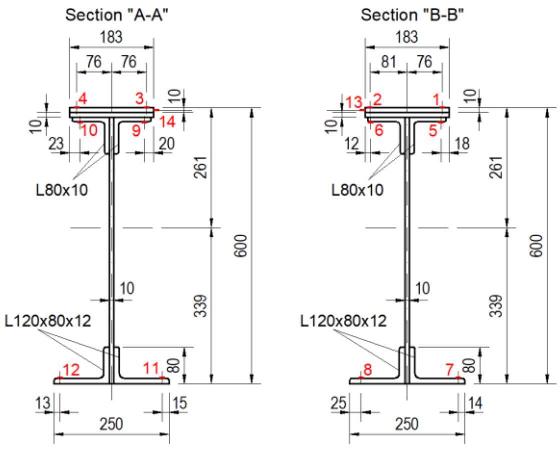

Fig. 3. Sections of the longitudinal girders and points of placement of the strain sensors

The main dimensions of the deck structure of the researched steel bridge and places of the placement of the sensors are shown in fig. 4

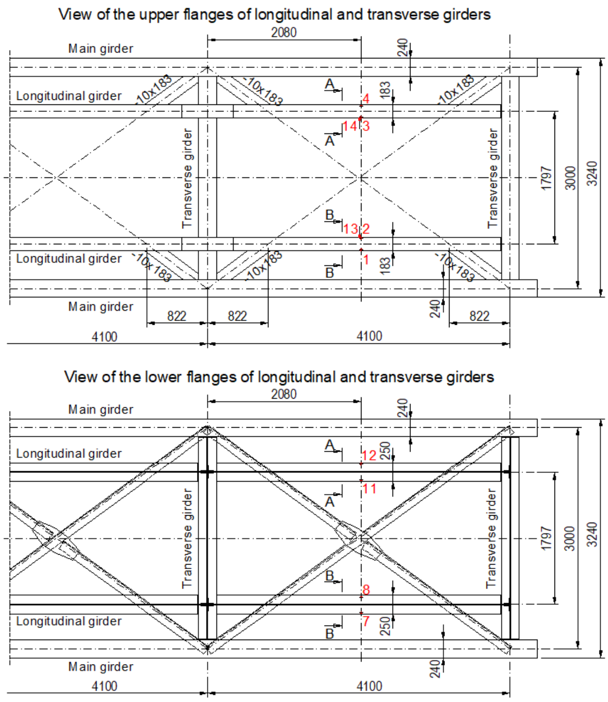

Fig. 4. Main dimensions of the deck structure of the bridge and points of placement of the sensors

The authors of the article did not find more information about the bridge as a designer, design standards, used steels, or year of commissioning.

3. Measurements

In 2021, the research team visited the selected bridge twice:

a) on 29.05, when he checked the status of those placed in 2020 strain gauge sensors 1-XY-6/120;

b) on 08.07 ÷ 10.07, during which the horizontal accelerations and the relative deformations in the transverse direction were measured in the middle of the upper flange of the two longitudinal beams in the last span. These accelerations and deformations are measured when passing through:

- ✓ single diesel locomotive, series 55;
- ✓ 5 (five) freight trains;
- ✓ 11 (eleven) fast passenger trains, consisting of an electric locomotive and 4 or 5 wagons;
- ✓ 9 (nine) slow passenger trains, of which:
  - 6 (six) consisted of a locomotive and 3 or 4 wagons;
  - 3 (three) were multiple-unit trains “Desiro” by the company “Siemens”.

Due to the greater overall weight and/or speed of passage of freight and fast passenger trains, nosing forces, generated by the slow passenger trains, have not been researched.

4. Determination of transverse nosing forces, based on measured strains in the flanges of the longitudinal beams

In the middle of the last span of the road deck, see fig. 3 and 4, strain gauge sensors 1-LY11-10/120 are placed on the flanges of the longitudinal beams, see fig. 5. Their scheme of electrical connection is a half-bridge. Through the sensors, at a recording frequency of 300 Hz, the relative deformations in the flanges of the longitudinal beams, which were caused by the passage of real trains, were measured in real-time.

a) cleaning of the flanges of the longitudinal beams

b) glueing of strain gauge sensors

Fig. 5. Preparation for placing strain gauge sensors

The corresponding shear forces and bending moments were calculated from the measured strains. On this basis can be calculated a fictitious bending force L_{calc} (applied at the level of the upper edge of the rail), which will lead to the realization of the determined forces:

$$L_{calc} = {k_L}^{-1}.R_{[3,1]}$$
$$\{R\} = E_a[A]^{-1}.\{e\}, \quad (1)$$

where:

$$\{R\} = \left[N, M_y, M_z\right]^T \quad (2)$$

$$\{e\} = \left[\varepsilon_i, \varepsilon_j, \varepsilon_k\right]^T \quad (3)$$

$$[A] = \begin{bmatrix} A_{\mathrm{l}ongg}^{-1} & z_i . I_{longg,y}^{-1} & y_i . I_{longg,z}^{-1} \\ A_{\mathrm{l}ongg}^{-1} & z_j . I_{longg,y}^{-1} & y_j . I_{longg,z}^{-1} \\ A_{\mathrm{l}ongg}^{-1} & z_k . I_{longg,y}^{-1} & y_k . I_{longg,z}^{-1} \end{bmatrix}, \tag{4}$$

in which:

$A_{\mathrm{l}ongg}, I_{\mathrm{l}ongg,y}, I_{\mathrm{l}ongg,z}$ are the cross-section and moments of inertia about axes "y-y" (horizontal) and "z-z" (vertical) of the longitudinal beam in the "open type" deck;

i, j, k – the numbers of the strain gauge sensors, used to measure the strain in the longitudinal direction for the respective points of the cross-section of the longitudinal beam, see fig.3 - 4;

z_i, z_j, z_k, y_i, y_j, y_k – the ordinates of points i, j, k to axes "z-z" and "y-y";

k_L – the bending moment to the vertical axis "z-z" in the cross-section of the longitudinal beam, caused by single force F_1 = 1 kN, applied in a horizontal direction on the level of the upper flange;

$R_{[3,1]}$ – element in 3 row, 1 column of the vector $\{R\}$;

E_a = 210 000 MPa – modulus of elasticity of the steel.

The relative deformations, on the basis of which the nosing forces are calculated, are measured in real-time, and for each instant of time the calculated fictitious nosing force is an algebraic number with a sign, indicating its direction. As follows, three basic values are obtained:

$\boldsymbol{Q}_{\mathbf{sk,tot,1}}$ – maximum value of the nosing force, calculated on the basis of the real-time measurements of the relative deformations along the longitudinal beam 1 - the right longitudinal beam (in the direction of movement);

$\boldsymbol{Q}_{\mathbf{sk,tot,2}}$ – maximum value of the nosing force, calculated on the basis of the real-time measurements of the relative deformations along the longitudinal beam 2 - the left longitudinal beam (in the direction of movement);

$\boldsymbol{Q}_{\mathbf{sk,tot}}$ – maximum value of the nosing force, calculated on the basis of the real-time measurements of the relative deformations along longitudinal beams 1 and 2. The values, obtained for the two beams, are summed at each moment in accordance with their signs, indicating the direction of the horizontal transverse impact at the corresponding moment of the time.

The values of the nosing forces, obtained by the relative deformations, are shown in Table 1 and graphically, in fig. 6 - 8.

By shown in Table 1 values of the nosing forces, obtained from the crossed eleven fast passenger trains, the following conclusions can be drawn:

a) the maximum values of transverse nosing forces do not exceed 26 kN for one longitudinal beam, see fig. 6;

b) the maximum value of the total nosing force, applied simultaneously to both longitudinal beams, does not exceed 21 kN.

By shown in Table 1 values of the nosing forces, obtained from the crossed five freight trains, the following conclusions can be drawn:

a) the maximum values of transverse nosing forces do not exceed 25 kN for one longitudinal beam, see fig. 7;

b) the maximum value of the total nosing force, applied simultaneously to both longitudinal beams, does not exceed 25 kN.

Table 1. Design trains and nosing forces generated by them, determined by considering the relative deformations, 07.08 – 07.10.2021

Train №	Type of train	Speed [km/h]	$Q_{sk,tot,1}$ [kN]	$Q_{sk,tot,2}$ [kN]	$Q_{sk,tot}$ [kN]	$Q_{sk,tot}/Q_{sk,EC1991-2}$
4 - 1	freight	58.0	20.222	19.960	20.091	0.166
4 - 2	passenger	-	1.481	1.814	1.648	0.014
4 - 5	passenger	-	16.358	25.575	20.967	0.173
4 - 6	passenger	72.0	9.304	8.057	8.681	0.072
4 - 8	passenger	67.0	11.900	12.683	12.291	0.102
4 - 12	passenger	67.0	9.778	9.931	9.855	0.081
5 - 1	freight	69.0	17.876	18.966	18.421	0.152
5 - 3	passenger	-	8.089	8.314	8.202	0.068
5 - 4	freight	-	16.282	18.582	17.432	0.144
5 - 5	freight	-	23.508	24.790	24.149	0.200
5 - 6	passenger	-	12.181	16.599	14.390	0.119
5 - 8	passenger	71.2	13.155	14.526	13.840	0.114
5 - 10	passenger	67.4	12.804	13.870	13.337	0.110
6 - 2	passenger	80.0	8.369	9.084	8.727	0.072
6 - 3	freight	60.0	16.754	17.625	17.190	0.142
6 - 4	passenger	71.0	11.975	15.719	13.847	0.114

$Q_{sk,EC1991-2}$ = 121 kN – the classified characteristic value of the nosing force, according to [3,4].

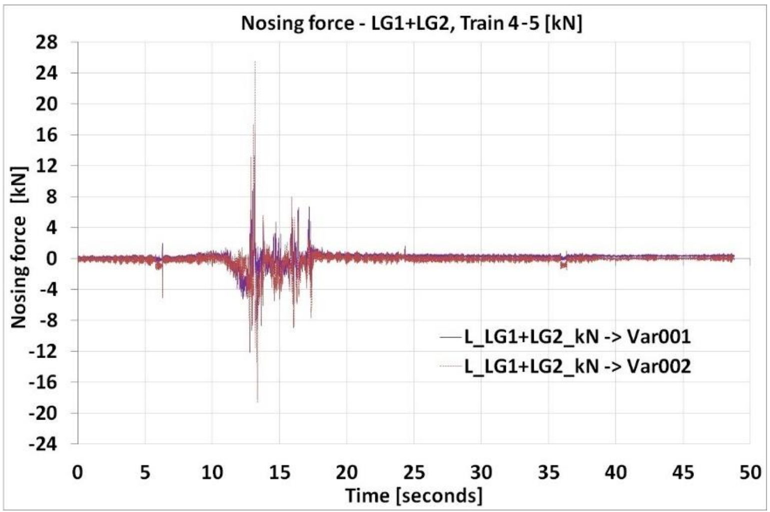

Fig. 6. Nosing forces due crossed passenger train 4-5

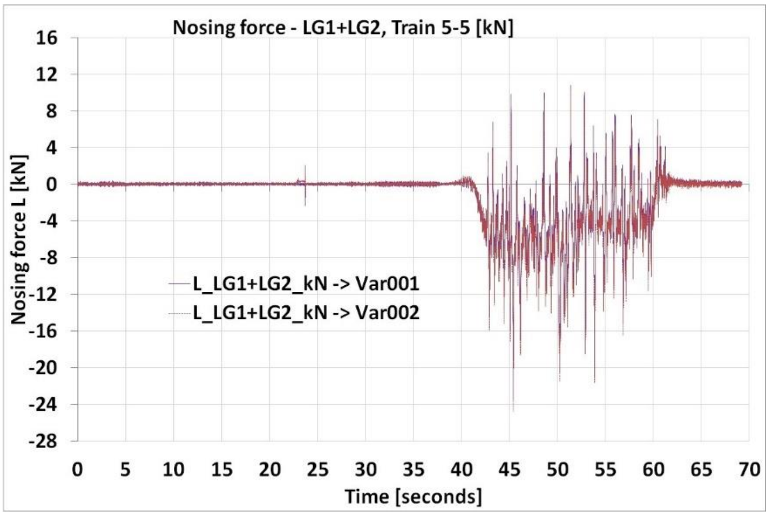

Fig. 7. Nosing forces due crossed freight train 5-5

The nosing forces, determined from the measurements, made on 08.07 – 10.07.2021, are not greater than those reported in 2020 [6].

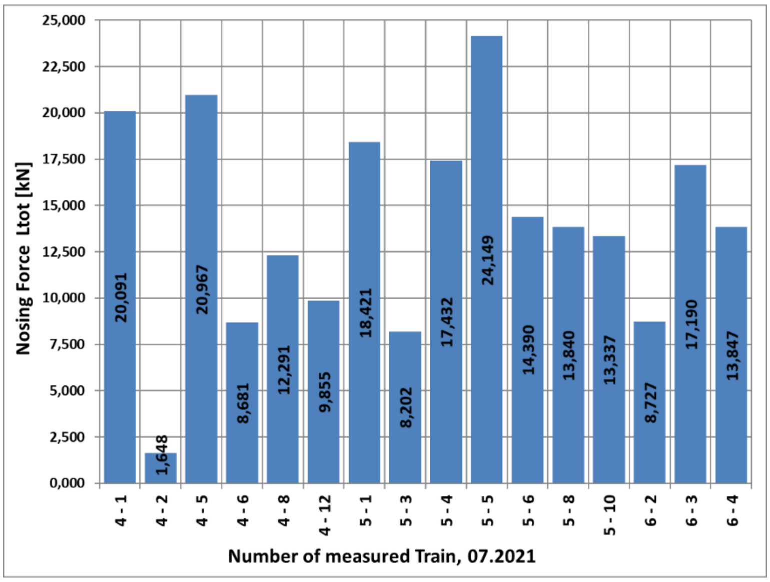

Fig. 8. Total value of nosing forces in the two longitudinal beams of the bridge, accounted by the strains in the flanges of the beams

The presence at the same moment of time of nosing forces with a different sign in each of the longitudinal beams, as well as the coincidence of the peaks of the diagrams in time, show that the wooden sleepers have a certain redistributive role, but this is not enough to equalize the transverse forces in the two longitudinal beams at larger values.

5. Determination of transverse nosing forces, based on measured horizontal accelerations in the upper flanges of the longitudinal beams.

In addition to strain gauge sensors 1-LY11-10/120, accelerometers are placed on the upper flanges of the longitudinal beams to measure the accelerations. Through them, the transverse horizontal accelerations, caused by the passage of railway trains, were recorded. After appropriate processing, from these accelerations can be obtained the transverse horizontal displacements, and from them - the corresponding nosing forces can be calculated. The methodology was developed by Ch. Assist. Prof. *N. Kerenchev*, Dr. Eng. It briefly includes:

a) evaluation of the signal by Fast Fourier Transform (FFT) and spectrogram analysis;

b) filtering of the high frequencies, which have low amplitudes and are not significant for the construction. In this case, a Butterworth filter is applied;

c) a velocigram is obtained by integrating from an accelerogram;

d) removal of low-frequency components, obtained during integration;

e) determination of the displacements.

The obtained by this methodology results are shown in Table 2. It can be seen that the accounted values of the nosing forces are greater than those, determined by strain gauges:

a) during the passage of freight train №. 5-1, the transverse forces reach almost 65 kN for one longitudinal beam;

b) the total nosing force, applied simultaneously to both longitudinal beams in the same train № 5-1 is almost 61 kN.

On the other hand, there is no difference in the maximum values of the nosing forces for one beam due fast passenger trains. They do not exceed 26 kN by both methods of determination. Comparing the nosing forces, determined by strain gauges and by accelerometers, train by train and girder by girder, the following is striking:

a) for the freight train № 5-1, the difference in the forces is more than three times in favour of the method, based on transverse accelerations.

b) for the fast passenger train № 5-4 there is an almost complete coincidence in the values for one beam and for the overall transverse impact, see Tables 1 and 2;

c) there is no dependence on the "divergence" of the values of the nosing forces, determined by the two methods.

It is also evident from Table 2 that the results do not exceed the standardized values in the "Standard for the design of road and railway bridges and culverts" from 1990 [1], and are about 40% lower than the standardized values in BDS EN1991-2:2006 [3].

In the previous study by the authors [6], the transverse nosing forces were determined by measuring the transverse displacements of the longitudinal beams and the relative deformations in them. The differences in the calculated values, determined by these two methods were relatively small. Therefore, we consider that in this case, the values of the nosing forces, shown in Table 1, are probably closer to the real impact and the methodology, based on the horizontal accelerations, needs further refinement. For this purpose, to calibrate the calculations from the records of the accelerometers, it is planned to simultaneously measure them in real-time during the passage of railway vehicles and the horizontal displacements at the corresponding points of the upper belt of the longitudinal beams. The latter is planned to be carried out through the installation of a suitable steel structure, which will be the basis for attaching sensors for measuring linear displacements in the horizontal transverse direction.

Table 2. Design trains and nosing forces generated by them, determined by considering the horizontal accelerations, 07.08 – 07.10.2021

Train №	Type of train	Speed [km/h]	$Q_{sk,tot,1}$ [kN]	$Q_{sk,tot,2}$ [kN]	$Q_{sk,tot}$ [kN]	$Q_{sk,tot}/Q_{sk,EC1991-2}$
4 - 1	freight	58.0	-	-	-	-
4 - 2	passenger	-	-	-	-	-
4 - 5	passenger	-	-	-	-	-
4 - 6	passenger	72.0	-	-	-	-
4 - 8	passenger	67.0	-	-	-	-
4 - 12	passenger	67.0	-	-	-	-
5 - 1	freight	69.0	64.26	38.62	60.92	0.503
5 - 3	passenger	-	16.34	13.85	23.37	0.193
5 - 4	freight	-	16.58	13.74	17.41	0.144
5 - 5	freight	-	43.59	28.81	46.7	0.386
5 - 6	passenger	-	14.85	13.80	18.84	0.156
5 - 8	passenger	71.2	25.34	12.07	23.57	0.195
5 - 10	passenger	67.4	22.17	15.16	16.17	0.134
6 - 2	passenger	80.0	13.24	13.02	16.68	0.138
6 - 3	freight	60.0	31.6	22.78	27.91	0.231
6 - 4	passenger	71.0	24.04	13.23	17.38	0.143

6. Conclusions

The horizontal impact of the fluctuating movements of railway vehicles in the transverse direction has a complex nature and impact on the elements of the road construction of open-type railway bridges. The consideration of this complex in nature impact in the design standards is realized by applying in the most unfavourable position a transverse horizontal force at the level of the upper edge of the rail. Prescribed values vary widely – 60 kN [1], 100 kN [2] and 121 kN [3,4], without taking into account the nature of the traffic and the design speed of the railway vehicles. During a number of measurements, carried out on an old steel riveted bridge at km. 18^{+985} of the Second railway line (Sofia - Mezdra - Varna), at a maximum vehicle speed of about 70 km/h, the following maximum values of the winding forces have been established:

a) when passing passenger trains – 26 kN for one longitudinal beam;
b) when passing freight trains – 30 kN for one longitudinal beam.

It could be seen that in the specific conditions of the conducted experiment - a steel bridge with an open type road structure and at relatively low speeds of railway vehicles (up to 130 km/h is allowed in European practice for freight trains), the requirements of [2] and [3,4] are conservative. Standard's prescribed values are about 3 ÷ 4 times higher than those determined by measurements and calculations for real railway traffic.

Almost all old steel railway bridges in service in the Republic of Bulgaria have an open-type road structure. They were designed and entered into an operation from the end of the XIX to about the middle of the XX century. Back then, nosing forces were not taken into account in the design of railway bridges. In present days, some of these bridges are in relatively good general condition, with no need for strengthening the road structure. It is recommended to carry out additional studies in the direction of the possibilities for an adequate reduction of the prescribed values of the nosing forces Q_{sk} in the future editions of BDS EN 1991-2 for existing bridges, as it is possible to take into account the relationship with the design speeds of vehicles, passing on the railway infrastructure.

Acknowledgements

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