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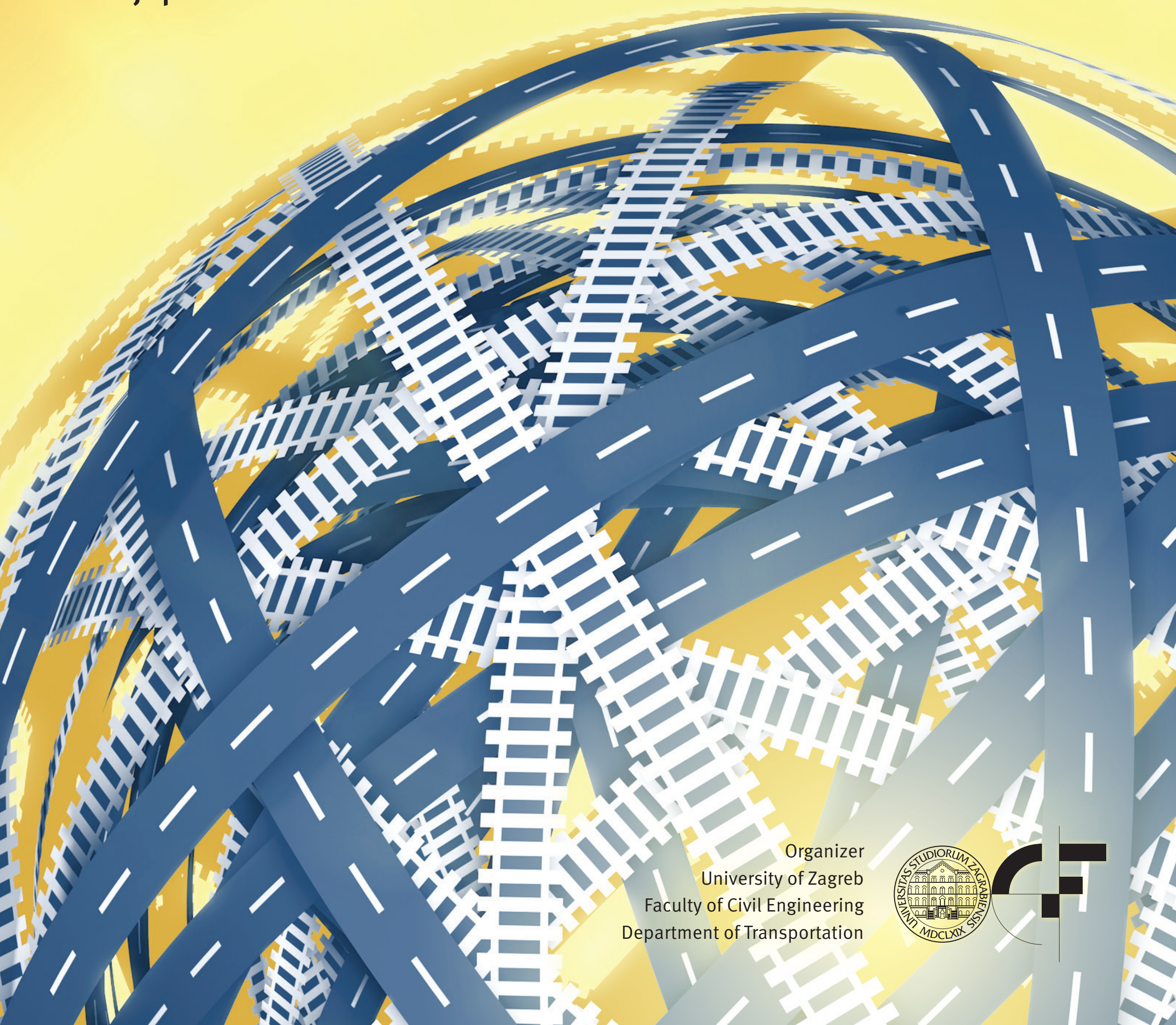
23–25 May 2016, Šibenik, Croatia

Road and Rail Infrastructure IV

Stjepan Lakušić – EDITOR



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EDITOR
Stjepan Lakušić
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Zagreb, Croatia

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STATIC AND DYNAMIC TESTING OF STEEL RAILWAY BRIDGE "SAVA"

Domagoj Damjanović, Janko Koščak, Ivan Duvnjak, Marko Bartolac
University of Zagreb, Faculty of Civil Engineering, Zagreb

Abstract

Due to the increase in traffic load, steel railway bridge "Sava" in Zagreb was strengthened in order to meet higher standard requirements. After the strengthening, experimental investigation of the bridge was conducted. Bridge "Sava" is a double-track railway bridge over 4 spans with total length of 306 m and width of 9.6 m. Static system of the bridge is a simply supported continuous beam which is strengthened by the arch in the main span (langer beam). The main span is 135.54 m long and the remaining three spans are 57.50 m, 57.96 m and 55.00 m long. Static and dynamic loading was performed using two 119.5 m long train compositions each consisting of locomotive (4 axles, 20.0 t per axle) and 8 freight wagons (4 axles, 19.95 t per axle). During the static testing trains were positioned in different locations on the bridge in order to achieve maximal inner forces and displacements. Displacements were measured at 30 measuring points and strains were measured at 16 measuring points. Within dynamic testing, modal parameters of the bridge (natural frequencies and modal shapes) were determined using operational modal analysis during ambient excitation. In addition, natural frequencies were determined from vibrations measured with robotic total station after train compositions pass by at various speed. Experimentally determined displacements, strains (stress) and modal parameters were compared to the corresponding numerical values obtained from the FE model of the bridge. Values of experimentally determined parameters presented in this paper are important for future monitoring of the structural health of the bridge structure.

Keywords: static and dynamic testing, structural health monitoring, operational modal analysis, modal parameters

1 Introduction

The railway bridge "Sava" was built in 1939 as a replacement for an old single-track railway bridge that was no longer able to sustain continuously increased traffic loads. Static system of the old bridge was a continuous truss girder over 8 spans with total length of 253 m, Figure 1 [1].

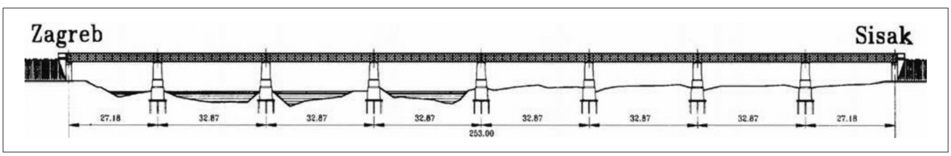

Figure 1 Old single-track railway bridge "Sava" [1]

The new bridge "Sava" is a double-track railway bridge over 4 spans with total length of 306 m and width of 9,6 m. Static system of the bridge consists of a continuous beam that is strengthened with arch in the main span (Langer beam). the link between the arch and the beam is achieved by 28 vertical steel hangers. The main span is 135,54 m long and the remaining three spans are 57,50 m, 57,96 m and 55,00 m long, Figure 2 [2].

Figure 2 New bridge "Sava" before the strengthening

Due to the increase in traffic load, steel railway bridge "Sava" needed to be strengthened in order to meet higher standard requirements in relation to those when bridge was built (1939). After the strengthening of the bridge had been performed, the experimental investigation of its static and dynamic characteristics was conducted [3]. The experimental investigation was fully performed according to guidelines given in Croatian National Standard HRN U.M1.046 – Testing of bridges with test load [4].

2 Testing of the bridge with test load

The main objective of the conducted experimental investigation was to determine whether the bridge "Sava" could withstand increased traffic load imposed on it after the strengthening. In this chapter, a brief description of experimental investigation is presented and measuring points of the investigated parameters are shown.

2.1 Progress of the experimental investigation

Experimental investigation consisted of static and dynamic testing. All static tests were conducted under the traffic load, which was in the form of locomotives and freight wagons, Figure 3. During the static tests, trains were positioned in different locations on the bridge in order to achieve maximum inner forces and vertical displacements corresponding to those from the bridge design data. Basic parameters and brief description of train compositions used for static loading of the bridge are shown in Table 1. Static testing of the bridge was carried out through multiple phases of loading and unloading. Vertical displacements were measured in each phase by a method of geometric levelling and by a trigonometric levelling method, Figure 4.

Table 1 Length and masses of train compositions used for static loading

Number of compositions = 2					
Locomotive (per composition)			**Wagons (per composition)**		
Number	Length	Mass	Number	Length	Mass
1	15,5 m	80,0 t	8	13,0 m	79,8 t
Total length per composition		15,5 + 8*13,0 = 119,5 m			
Total load per composition		80,0 + 8*79,8 = 718,4 t			
Total load		**718,4*2 = 1436,8 t**			

Figure 3 Static testing of the bridge “Sava” – two compositions in the main span

During the static testing, strains in critical elements were measured via LVDT sensors and the data was collected with the HBM MGCPlus data acquisition system, providing continuous measurement with the adjustable sampling frequency. With that possibility strain measurement was conducted while compositions were moving across the bridge at low speed in order to identify the maximum values of inner forces occurring in the bridge elements.

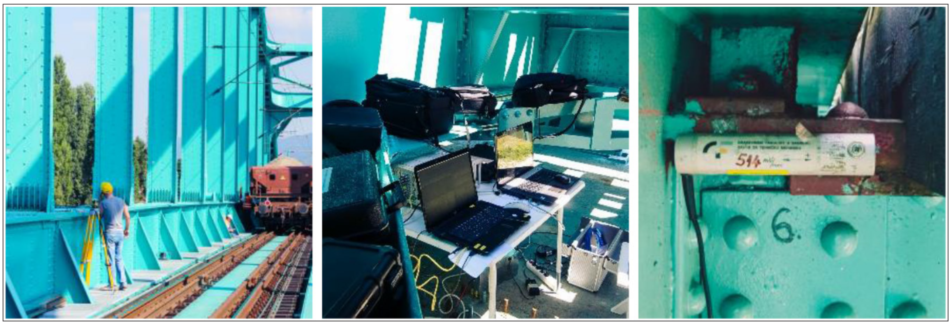

Figure 4 Vertical displacement measurement (left), data acquisition system (middle) and strain measurement sensor (right) on bridge “Sava”

Modal parameters (natural frequencies and modal shapes) were determined by means of operational modal analysis. Accelerations were measured in multiple measuring points on the bridge during ambient excitation, using accelerometers (PCB Piezotronics 393B31) – connected to the Bruel & Kjaer 3560C data acquisition system. Two accelerometers were used as reference, while the other two were moved through all measuring points. Acquisition and post processing of the data was conducted on PC with the Bruel & Kjaer “Pluse” software. Data post processing included Fast Fourier Transforms (FFT) and Frequency Domain Decomposition (FDD) of the time signal functions measured with accelerometers in order to obtain bridge modal shapes. Detailed explanation of data post processing procedure is shown in [5] and [6].
Unlike the operational modal analysis, determination of natural frequencies with the robotic total station is hardly achievable during the ambient excitation only. For that reason higher level of vibration of the bridge were produced by train passing over the bridge at various speed [7], [8].
It is important to note that the experimental investigation was fully performed according to guidelines given in Croatian National Standard HRN U.M1.046. Please note that not all of the performed tests and obtained results are shown in this paper. Rather, the presented results are limited to vertical displacements, strains in critical elements and modal parameters. Critical values of the measured vertical displacements and determined modal parameters are compared to the values obtained from numerical models, which are based on FEM [9].

2.2 Investigated parameters

During the experimental investigation of the bridge “Sava” vertical displacements of the bridge were measured at 30 measuring points (namely, 21 measuring points along axis A and 9 measuring points along axis B), see Figure 5. Vertical displacements were measured by the modified method of geometric levelling and also by the trigonometric levelling method.

Table 2 Measuring points for strain measurement

Measuring point label		Description of the measuring point location
S1	MG1-LZ	Main girder, span 1, lower flange.
S2	MG2-LZ	Main girder, span 2, lower flange.
S3	MG2-UZ	Main girder, span 2, upper flange.
S4	CG2 – UZ	Cross girder, span 2, upper flange.
S5	CG2 – UZ2	Cross girder, span 2, upper flange.
S6	SLG2 – UZ	Secondary longitudinal girder, span 2, upper flange.
S7	HM	Hanger in the middle of the main span.
S8	H2	Second hanger.
S9	H1N	First hanger, north side.
S10	H1S	First hanger, south side.
S11	ARCH	Arch, span 2, south side.
S12	MG2C – UZ	Main girder, column between 2. and 3. span, upper z.
S13	MG3 – LZ	Main girder, span 3, lower flange.
S14	MG4 – LZ	Main girder, span 4, lower flange.
S15	SLG3C – LZ	Secondary longitudinal girder, span 3 – near column.
S16	CG2C – UZ	Cross girder, column between 2. and 3. span.

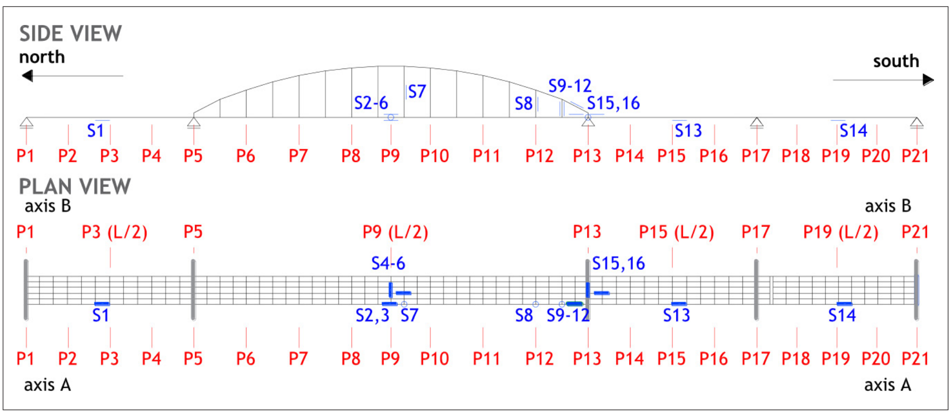

Figure 5 Measuring points of static vertical displacements (red) and measuring points for strain measuring (blue)

Apart from vertical displacements, strains in critical structural elements were measured at 16 measuring points continuously during all phases of static testing of the structure. Measuring points for strain measurement were placed on main girders (6 measuring points), on the secondary longitudinal and cross girders (5 measuring points) and on the arch and hangers of the main, largest, span (5 measuring points), Figure 5 and Table 2.

Within determination of modal parameters (natural frequencies and modal shapes) using OMA, accelerations were measured at 42 points during ambient excitation. Additionally, natural frequencies of the bridge were determined from the vibration measured with the Robotic Total Station (RTS). Positions of the acceleration measuring points (1-42) as well as RTS measuring point are shown in Figure 6.

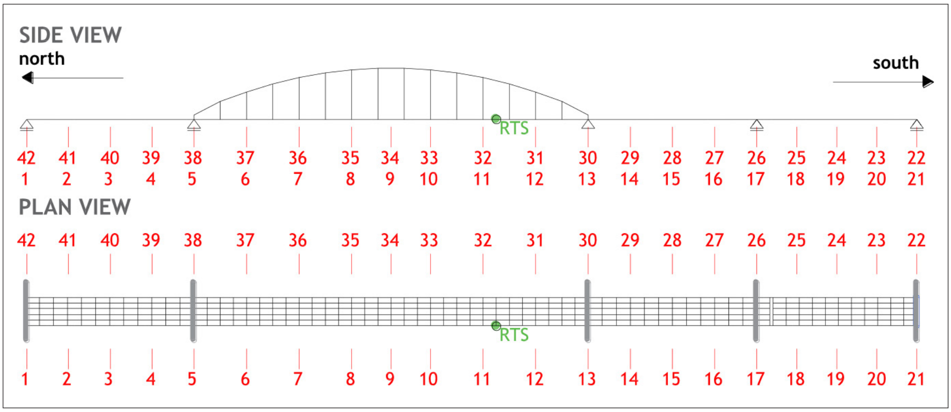

Figure 6 Positions of accelerometers and RTS measuring points

3 FEM modelling of the bridge

Vertical displacements and modal shapes obtained by experimental investigation are compared to those obtained from numerical model. Numerical model of bridge "Sava" was created in software CSI SAP2000 v18 based on Finite Element Method (FEM). Figure 7 shows numerical model of the bridge created with frame elements.

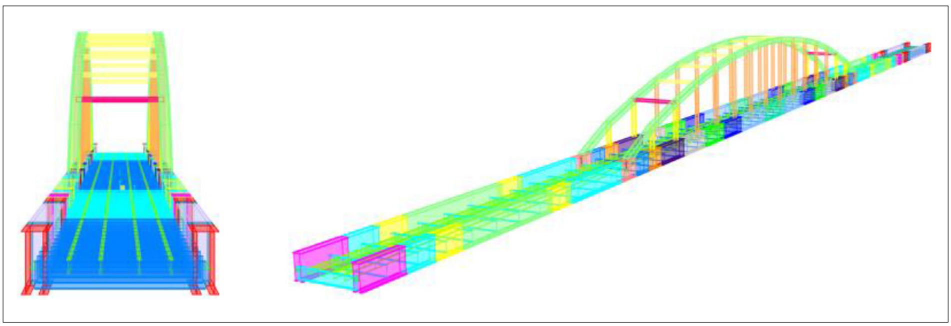

Figure 7 FEM numerical model of the bridge "Sava" – 3D view

In order to determine masses and positions of train compositions causing maximum inner forces and displacements of the structure, numerical models were made prior to experimental investigation. For all numerical models static and dynamic analysis was conducted. Within the static analysis, forces equal to those of train compositions were applied on to the numerical models. Analysis output in terms of vertical displacements is compared to experimentally obtained values and presented in this paper. Furthermore, dynamic analysis was conducted and dynamic parameters (natural frequencies and modal shapes) obtained from a numerical model are compared to measured ones.

4 Results

4.1 Vertical displacements

In this paragraph, maximum values of measured vertical displacements for each span of the bridge are compared to corresponding numerically obtained displacements. Residual values after load removal were also measured and shown below.

Table 3 Comparison between measured and numerically obtained vertical displacements

Span	Measuring point	Measured value	Calculated value	Residual displacement
1	P3-A	45,0 mm	47,6 mm	2,0 mm
2-main span	P9-B	102,0 mm	107,0 mm	2,0 mm
3	P15-A	43,0 mm	49,0 mm	1,0 mm
4	P19-B	49,0 mm	51,2 mm	1,0 mm

Table 3 and Figure 8 show that results obtained from experimental investigation are similar to those obtained from numerical model. Maximum deviation between measured and calculated values is about 12 % (span 3). Maximum residual displacement is measured in spans one and two (2,0 mm), which is 4 % of maximum measured displacement in span 1 and 2 % of maximum measured displacement in the main span. Ratio between residual and maximum measured vertical displacements is below 15 %, which is maximum allowed value given in Croatian National Standard HRN U.M1.046 for steel structures.

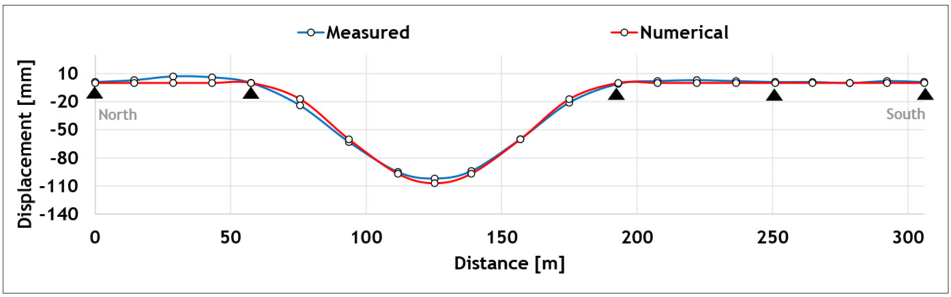

Figure 8 Measured and numerically obtained deflection curves for a load case with two compositions in the main span – max. vertical displacement

4.2 Strain measurement

Due to determination of cross section usability, strain measurement was conducted within the experimental investigation. Maximum measured strain value detected during experimental investigation was -0,3793 ‰ at measuring point S11-ARCH which is, from expression (1), stress of -79,7 MPa. Continuous record of strain measured values during experimental investigation is shown in Figure 9. Stress estimation is calculated with the Hooke's law for one axial stress,

$$\sigma = \varepsilon \cdot E \tag{1}$$

where ε represents measured strain value, E [MPa] is young's module of elasticity and σ [MPa] represents calculated stress value. Expression (1) can be used if all sensors were placed in one axial stress zone, which is the case in this experimental investigation.

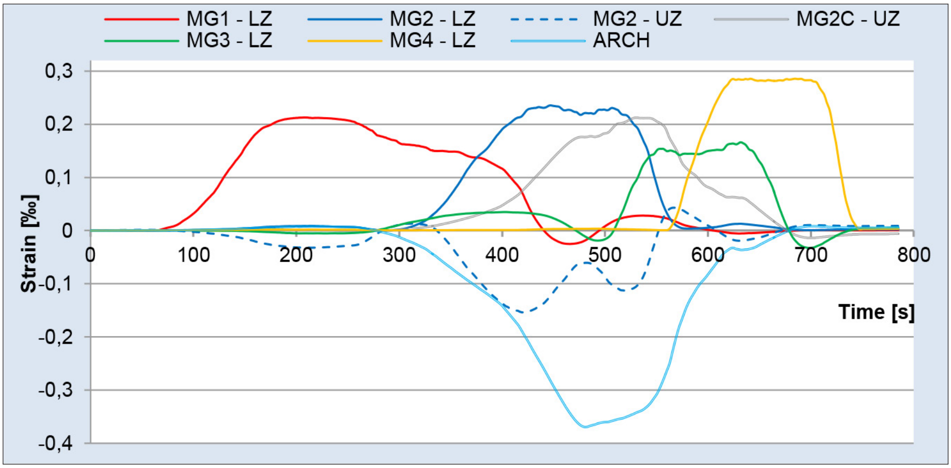

Figure 9 Continuous record of strain measured values during experimental investigation – measuring points on the main girder

4.3 Dynamic parameters

Natural frequencies of the bridge were determined from dynamic displacement measured by robotic total station (RTS) and with operational modal analysis (OMA). Fast Fourier transform (FFT) analysis was used to convert the time domain records of dynamic displacement measured by RTS to frequency domain. Natural frequencies were identified as resonance peaks of these spectral functions. Comparison between measured and numerically obtained values are shown in Table 4.

Table 4 Natural frequencies of the bridge "Sava"

OMA [Hz]	RTS [Hz]	Numerical model [Hz]
1,01	1,02	1,03
1,57	1,56	1,63
1,96	1,95	1,54
2,73	2,73	2,81

For each natural frequency modal shape was also determined by operational modal analysis, some of experimentally obtained modal shapes are shown below.

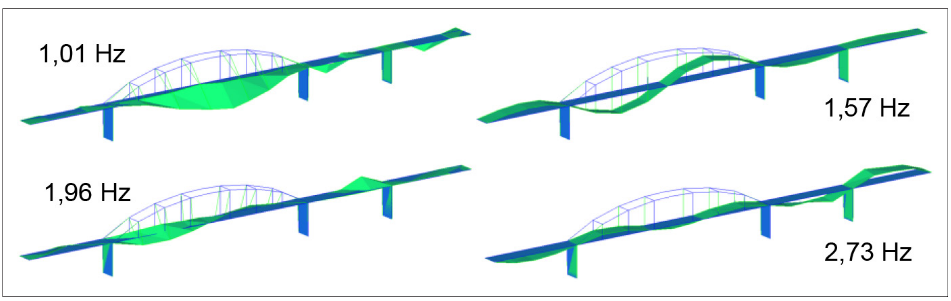

Figure 10 Modal shapes of the bridge obtained my operational modal analysis

5 Conclusions

The steel railway bridge "Sava" was strengthened in order to meet higher standard requirements in relation to those when the bridge was built. After the strengthening was done, experimental investigation of the bridge static and dynamic parameters was performed according to the guidelines given in the Croatian National Standard HRN U.M1.046 – Testing of bridges with test load [4]. The experimental investigation consisted of vertical displacement and strain measurement but also of dynamic parameters determination. Comparison between numerically obtained and measured values of vertical displacements shows high accordance in results. Furthermore, measured values of residual vertical displacements were below 15 % of the maximal measured values, which is maximum allowed ratio for steel structures given in the HRN U.M1.046 standard. Measured strain and estimated stress show that all critical structural elements of the bridge remain elastic during all phases of static tests. Maximal measured strain value was -0,379 ‰ which gives stress of 79,7 MPa or 22,5 % of yielding point value for steel S355 which is the main construction material of the bridge. Investigated dynamic parameters are of great importance for the future health monitoring of the structure. Dynamic parameters obtained from experimental investigation are within the expected range, which indicates that no damage occurred during the experimental investigation and that the strengthening of the bridge can be overall assessed as successful.

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