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Load testing of the Svilaj interstate bridge

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Abstract: The paper presents static and dynamic load testing of the Svilaj interstate bridge over the Sava River. In addition to presenting the basic structural elements of the bridge, the paper briefly describes the testing method, provides the basic characteristics of the equipment used for testing, and presents some of the results of the conducted testing along with an analysis and comparison of the measured parameters. At the end of the paper, the conclusion explains that a high level of agreement between the measured parameters was determined and the performance of the structure was verified.

Key words: bridges, load testing, oscillation frequencies, displacements, stresses

Ispitivanje probnim opterećenjem međudržavnog mosta Svilaj

Sažetak: Članak prikazuje statičko i dinamičko ispitivanje probnim opterećenjem međudržavnog mosta Svilaj preko rijeke Save. Uz prikaz osnovnih konstruktivnih elemenata mosta, u članku je ukratko opisan način ispitivanja, date su osnovne karakteristike primijenjene opreme korištene za ispitivanje te su prikazani neki od rezultata provedenog ispitivanja, uz analizu i usporedbu izmjerenih parametara. Na kraju rada, kroz zaključak je pojašnjeno kako je utvrđena visoka razina podudarnosti izmjerenih parametara te je verificirana izvedba građevine.

Ključne riječi: mostovi, ispitivanje probnim opterećenjem, frekvencije osciliranja, pomaci, naprezanja

1. INTRODUCTION

This paper presents the results of load testing conducted on the Svilaj interstate bridge over the Sava River, which is an integral part of the international Pan-European road corridor Vc Budapest - Beli Manastir - Osijek - Sarajevo - Ploče (Figure 1). Corridor Vc is part of the European highway network, designated as E-73, which connects northern Europe with the Adriatic and forms the backbone of road infrastructure in the eastern part of Croatia. The bridge over the Sava River is also a contact point of the highway networks of the Republic of Croatia and Bosnia and Herzegovina [1]. The construction work on the bridge was carried out by the company Hering d.d. Široki Brijeg. It began in September 2016 and was completed in July 2020 (Figure 2). The bridge was opened to traffic on September 30, 2021 [2].

Figure 1. - Location of the Svilaj bridge on Corridor Vc

Figure 2. - Svilaj bridge

According to the standard designated as U.M1.046 from 1984, derived from the JUS standard [3] which is applicable in Bosnia and Herzegovina, or HRN U.M1.046 [4] which is applicable in the Republic of Croatia, road bridges are subject to testing under static and dynamic loads. The effect of the test load must, to a certain extent, correspond to the effect of the moving load applied in the static analysis, in accordance with the specified standard [5].

In accordance with the applicable rules, load testing of bridges is one of the requirements for technical inspection and issuance of an operating permit and it applies to road bridges with spans greater than 15 meters and railway bridges with spans greater than 10 meters. The load testing of the Svilaj bridge was carried out by staff of the Faculty of Civil Engineering, Architecture and Geodesy, University of Mostar, in cooperation with staff of the Faculty of Civil Engineering, Architecture and Geodesy, University of Split. The testing determines the response of the structure to specific static and dynamic loads, as specified in the design [6].

2. DESCRIPTION OF THE BRIDGE STRUCTURE

The description of the bridge structure is based on the Technical Report for the bridge design, prepared by the company "IPZ" Zagreb.

The bridge superstructure is a continuous beam over seven spans with a double-composite cross section consisting of a steel box and a concrete bottom (along the supports) and top (deck) slab. Two identical structures were constructed for the left and right roadway of the highway. The spans of the superstructure are 70.0 + 85.0 + 100.0 + 130.0 + 100.0 + 85.0 + 70.0 = 640.0m between the abutment axes (Figure 3). The total width of the bridge is 13.5+2.0+13.5=29.0m. The design specifies three 3.5m traffic lanes without an emergency lane, with 0.5m safety strips on both sides of the roadway, so that the width of the asphalt surfacing is 12.0m. This is followed by a granite curb and a monolithic concrete sidewalk with a total width of 0.75m, widened by an additional 0.45m at the location of the lighting pole. A rigid BN4-type guardrail, 0.40m wide and 1.0m high, is planned at the ends of the cantilevers. Pedestrian traffic is not anticipated on the bridge.

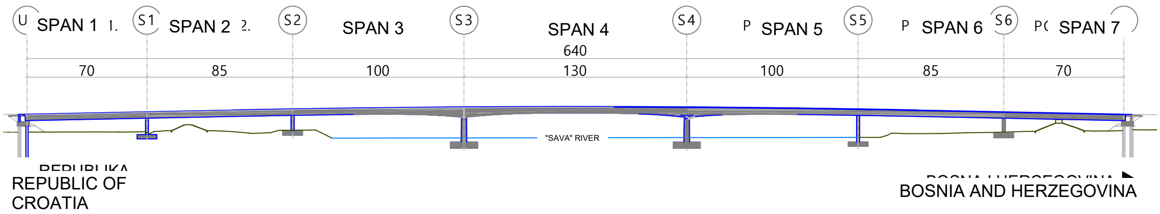


Figure 3. - Longitudinal section of the Svilaj bridge

The entire bridge is a single expansion unit, with expansion joints located only at the abutments. At each pier foundation, the superstructure has a single massive pier on which two bearings rest. The bearings are constructed as pot bearings, all longitudinally movable except at pier S3, which alone receives the slow loads from temperature and rheology.

A composite box girder with a variable height from 3300 to 5500mm was selected for the cross section of the continuous structure. The box section has a horizontal bottom slab stiffened with torsionally rigid trapezoidal ribs, while the top concrete slab is transversely inclined by 2.5%. The thickness of the bottom slab varies from 16 to 50mm (above the piers). The trapezoidal shape of the cross section is maintained by transverse frames spaced at approximately 4000mm intervals and with bracings spaced at approximately 12000mm intervals. The structure is supported by pot bearings, which are installed on blocks of fine-grained concrete.

The steel quality is S355J2G3 for all parts of the structure, the concrete of the deck slab is of class C35/45, the concrete of the bottom slab is of class C40/50, the reinforcement is of quality B500B, and the prestressing steel is of quality Pst 1660/1860 MPa.

The transversely prestressed reinforced concrete deck slab was made *in situ* in its full width of 12.9m. Above the main girder web, the slab thickness is 40cm, in the middle of the span 28cm, and at the end of the cantilever 25cm. The slab is connected to the steel box via stud connectors, which are welded to the box flanges. The main reinforcement in the slab is in the transverse direction of the bridge, and above the middle bearings (where the slab is in tension) in the longitudinal and transverse directions. The deck slab is prestressed in the transverse direction with unbonded 4x0.62" tendons, spaced at 0.5m.

Six piers were constructed, with varying dimensions, depending on the height, bearing arrangement, and loading. The piers have a solid elliptical cross section, the dimensions adjusted to the dimensions of the bearings at specific locations, and the river piers are constructed with sloping sides, for aesthetic reasons. Common foundations were constructed for piers S1 and S6, S2 and S5, and S3 and S4, each with 24 to 32 piles with a diameter of 150cm and a length of L=18.0m.

The abutments are monolithically constructed, horseshoe shaped, common to both bridges, with integrated expansion joints. The foundation is rectangular, measuring 28.2 x 6.95 x 2.5m, supported by 12 piles, each with a diameter of 150cm and a length of 18.0m. The bearing surface is inclined 2% toward the breast wall for drainage. The breast wall is 80cm thick, as are the wings.

3. TESTING PROGRAM

The behavior of the structure under static and dynamic traffic loads, the conformity of construction quality with the design requirements, and the ability of the structure to bear the designed loads are verified by load testing of the bridges.

In accordance with the specified rules and standards, the effect of the test load must correspond to a certain extent to the effect of the moving load applied in the static analysis. Since the static analysis uses the standard loads given in the relevant standards for the calculation of road bridges, and heavy trucks are used for load testing, the number and mass of the trucks must be determined to obtain adequate internal forces.

According to the Testing Program, which was prepared and subsequently approved by the supervisory authority and the designer [7], the load testing was carried out using a maximum of 12 heavy trucks, each with a mass of approximately 400 kN, positioned to induce the maximum stresses in all spans (Phase I) and over piers S4, S5 and S6 (Phase II). Load schemes were also developed to induce the maximum shear stresses in the bridge rib (Phase III) along the support for the left side of spans 5, 6, 7 and 8. For all load schemes in spans and above the supports, the position of the trucks is asymmetrical in order to determine the behavior of the bridge under such load (Figure 4).

First, one side of the bridge is loaded asymmetrically, and subsequently, a mirror-image loading is applied to the other side of the bridge. For the shear schemes, vehicles are positioned symmetrically on the longitudinal axis of the bridge, with three rows of three trucks, near the support. There are a total of nine vehicles here and only the symmetrical scheme is used. At the abutments, due to the high utilization coefficient of U2, the number of trucks is eight.

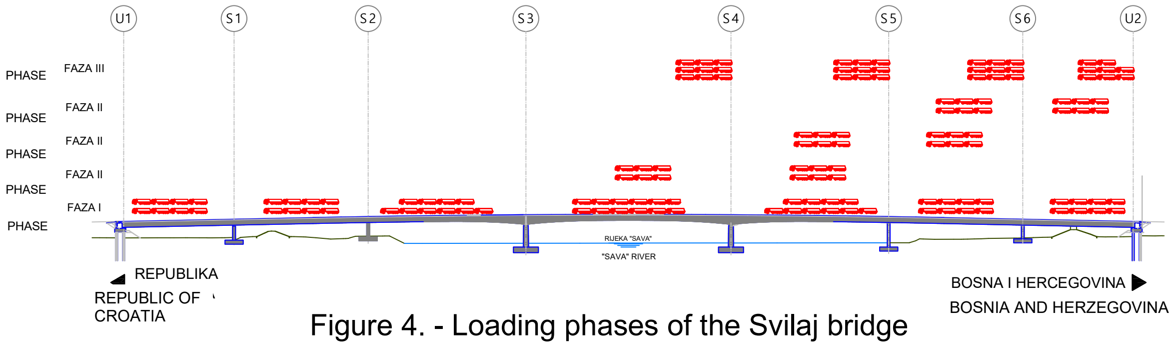


Figure 4. - Loading phases of the Svilaj bridge

According to the rules and standards used, the efficiency coefficient is the ratio of the effect of the design load to the effect of the actual test load applied by heavy trucks, and it must be between 0.5 and 1.0, which is satisfied for both structures of the Svilaj bridge (left and right). Specifically, the efficiency coefficients were between 0.76 and 0.86 for measuring the effect in the bridge spans, between 0.5 and 0.68 for measuring the effect on the piers, and between 0.52 and 0.81 for measuring the shear effect, depending on the test location and load scheme.

4. LOCATIONS OF MEASUREMENT POINTS AND EQUIPMENT USED

4.1 Locations of measurement points

In accordance with the previously briefly described Testing Program, a load testing was conducted where vertical displacements were geodetically measured in all bridge spans (Figure 5) at three points across the width of the roadway (Figure 6).

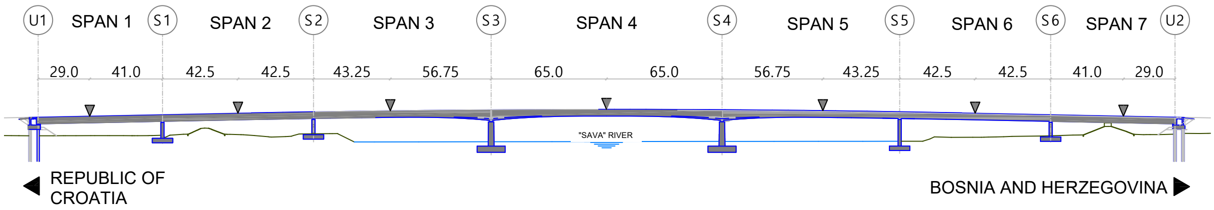


Figure 5. - Measurement points for measuring vertical displacements - longitudinal section

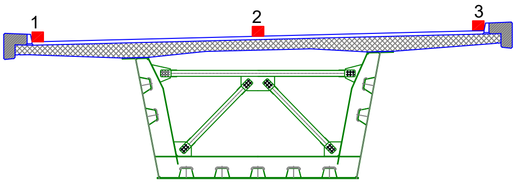


Figure 6. - Measurement points for measuring vertical displacements - cross section

In addition to vertical displacements measured in all bridge spans, strains were also measured using concrete and steel strain gauges in critical sections for spans 1 - 4 (Figure 7) and at piers S4, S5, and S6 (Figure 8).

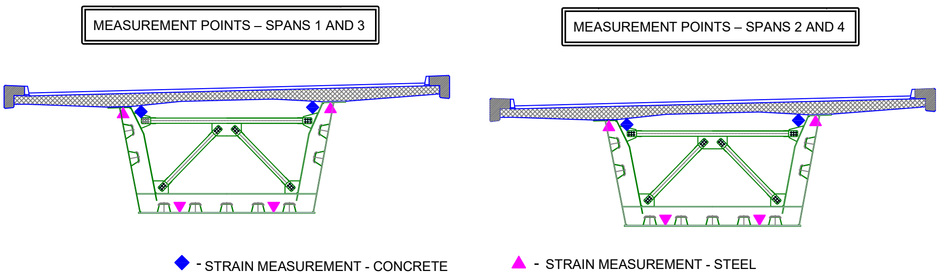


Figure 7. - Measurement points for measuring strains in spans 1-4

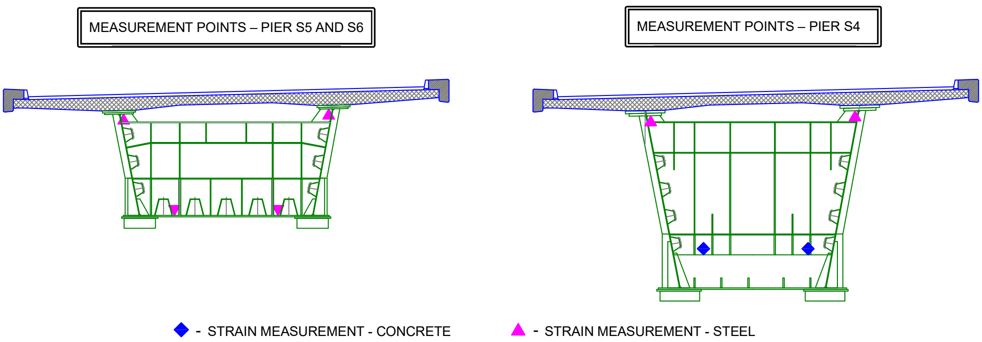


Figure 8. - Measurement points for measuring strains at piers

Strains were also measured in the zone of the change in flange thickness (Figure 9a) and change in web thickness (Figure 9b), in the area of abutment U2 and piers S4, S5, and S6, which are symmetrically arranged in the cross section where strain gauge rosettes were installed to determine the biaxial stress state in cases of unknown directions of principal stresses.

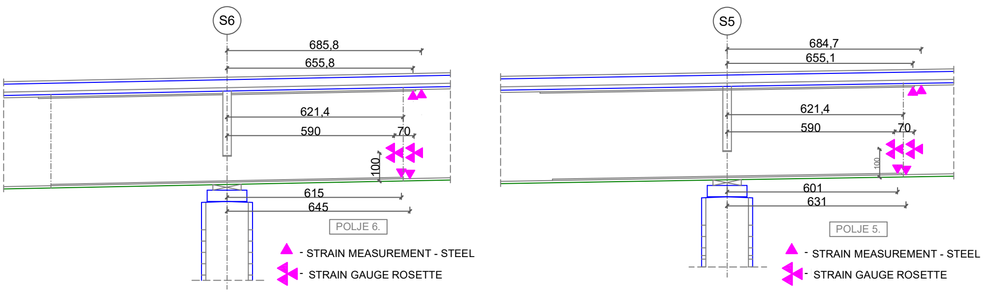


Figure 9a. - Measurement points for measuring strains for the changes in flange thickness and web thickness, S6 and S5

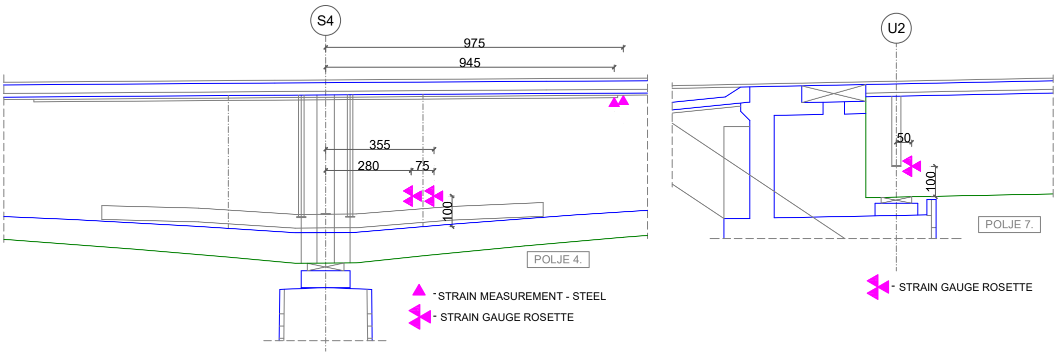


Figure 9b. - Measurement points for measuring strains for the changes in flange thickness and web thickness, S4 and U2

4.2 Measurement equipment used

On the Svilaj bridge, a total of 196 measurement points were observed, with strain gauges installed on the concrete or steel structure, or 98 measurement points on each of the left and right bridge structures.

For the measurement of strains in concrete, strain gauges manufactured by HBM, type K-LY41 1-15-120-0, were used, while the strains in steel were measured using HBM strain gauges type K-LY41 6/120 (Figure 10).

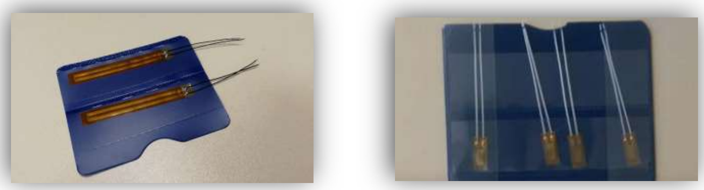


Figure 10. - Strain gauges for concrete (left) and steel (right)

Acceleration was measured using an acceleration transducer, namely an HBM uniaxial accelerometer, type B12/500 (Figure 11a). The measured values were collected using the

MGC plus (Figure 11b) and *Quantum X* (Figure 11c) systems, and were processed with the Catman AP software package. The maximum number of measurement points at one measurement location was 24 (Figure 12).

a) Acceleration transducer b) "MGC plus" device c) "Quantum X" device

Figure 11. - Measurement equipment used

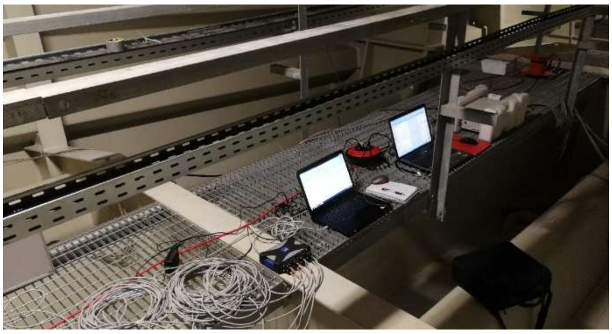


Figure 12. - Measurement equipment at the test site

5. RESULTS OF STATIC TESTS AND COMPARISON WITH CALCULATION

Static tests (Figures 13 and 15) were carried out according to the loading schemes presented in Chapter 3. The test results for vertical displacements and strains, taken from the Test Report [8], will be presented in the following text.

Figure 13. - Placing the load in position for static testing

5.1 Vertical displacements of the Svilaj bridge

Vertical displacements were measured using geodetic instruments at three points in the bridge cross section, as shown in Chapter 4, with measurements taken before, during and after the application of the test load.

The results obtained from the load testing were compared with the vertical displacements calculated using the Tower 3D software package [9] (Table 1). The calculation model was made as a spatial model.

Table 1. - Comparison of measured and calculated vertical displacements

		SPAN						
		1	**2**	**3**	**4**	**5**	**6**	**7**
MEASURED DISPLACEMENTS (mm)	1.	41.2	54.7	78.1	**136.5**	79.4	59.7	43.8
	2.	35.4	49.2	69.2	**125.2**	72.2	55.2	42.2
	3.	35.2	48.9	69.7	**124.9**	69.7	51.8	37.1
CALCULATED DISPLACEMENTS (mm)	1.	41.22	56.81	84.25	**151.92**	84.25	56.81	41.22
	2.	48.08	63.94	92.27	**162.06**	92.27	63.94	48.08
	3.	54.02	70.12	99.45	**171.55**	99.45	70.12	54.02

The maximum values for the middle point are shown below (Figure 14).

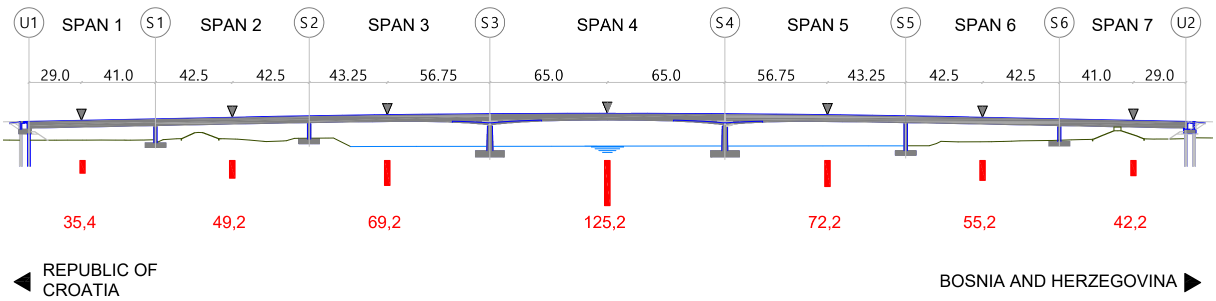


Figure 14.- Maximum vertical displacements in the middle of the roadway (mm)

Figure 15. - Load in the position for static testing

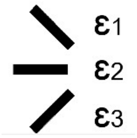
5.2 Svilaj bridge deformations

Since 98 strain gauges for measuring strains were installed on both the left and right bridge structures, the results of the measured strains in span 4, strains at abutment U2 and pier S6, and changes in the thickness of the flanges and web, also at pier S6, will be presented below.

The load test results are presented in tables and in diagrams obtained by processing the measured values in the Catman AP software package. Based on the measured strains and known values of the modulus of elasticity for concrete (MB50 and MB55) and steel, the stresses are determined according to the formulas:

- Steel stress: $\sigma = \varepsilon(‰) \cdot 210000(MPa)$
- Concrete stress (top slab, MB50): $\sigma = \varepsilon(‰) \cdot 36000(MPa)$
- Concrete stress (bottom slab, MB55): $\sigma = \varepsilon(‰) \cdot 37000(MPa)$

At the locations of changes in web thickness, strain gauge rosettes were mounted to determine the biaxial stress state where the principal directions (the directions of action of the principal stresses) are unknown. From the strains of these gauges, the principal stresses will be calculated according to the formula:



$$\sigma_{1,2} = \frac{E}{1-\vartheta} \cdot \frac{\varepsilon_1 + \varepsilon_3}{2} \pm \frac{E}{\sqrt{2}(1+\vartheta)} \cdot \sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_3 - \varepsilon_2)^2}$$

5.2.1 Strains for span 4

The strains in span 4 (Figures 16, 17, and 18) were measured at six measurement points according to the scheme presented in Chapter 4. The labels used for the measurement points are: BGL - concrete top left, BGD - concrete top right, CGL - steel top left, CDL - steel bottom left. After analyzing the measured results, a comparison of the obtained stress values was made (Table 2).

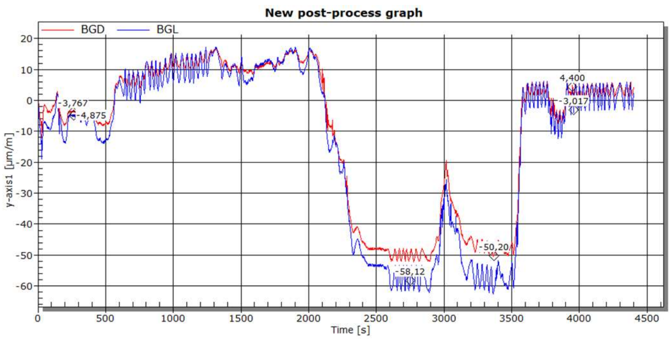


Figure 16. - Time history of strains for span 4 (concrete - upper side)

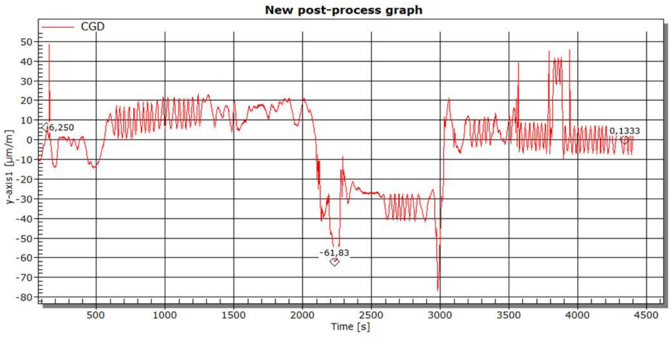


Figure 17. - Time history of strains for span 4 (steel - upper side)

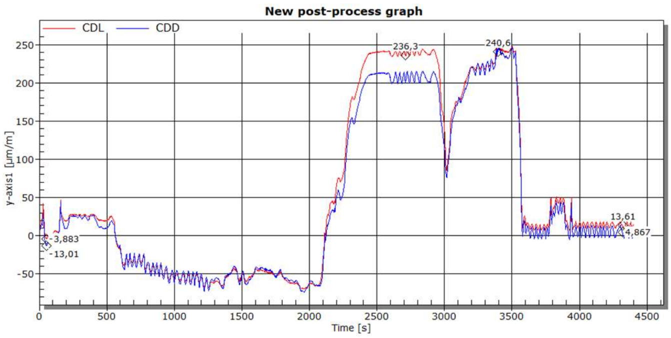


Figure 18. - Time history of strains for span 4 (steel - lower side)

Table 2. - Comparison of stresses for span 4

	BGL	BGD	CGL	CGD	CDL	CDD
Calculated stress (MPa)	-2.52	-2.52	-18.93	-18.93	+62.60	+62.60
Measured stress (MPa)	-1.67	1.91	-	-14.29	+50.42	+53.25

Note: The strain gauge at position CGL (steel-top-left) was not operational due to damage to the test cable. The strain gauges were connected to the measuring device and computer with special connectors (Figure 19).

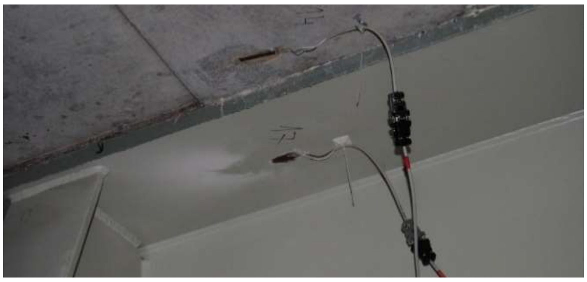


Figure 19. - Strain gauges for measuring strains on concrete and steel structures

5.2.2 Strains at abutment U2

The strains at abutment U2 (Figures 20 and 21) were measured using the strain gauge rosettes (Figure 22) from which the principal stresses were calculated and compared with the calculated results (Table 3).

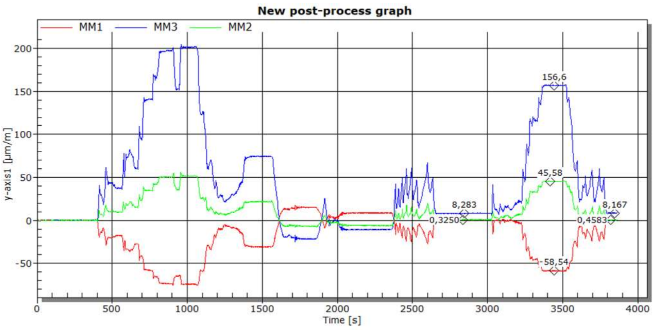


Figure 20. - Time history of strains for U2, web-left

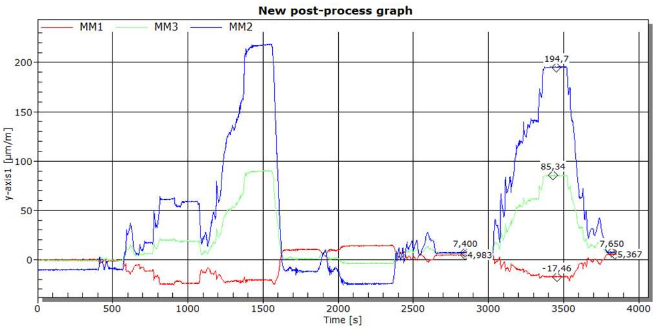


Figure 21. - Time history of strains for U2, web-right

Table 3. - Comparison of principal stresses for U2

	Principal stress (MPa)	LEFT	RIGHT
Calculated	σ_1	+20.74	+20.90
	σ_2	-27.62	-27.34
Measured	σ_1	+22.72	+32.44
	σ_2	-26.26	-17.36

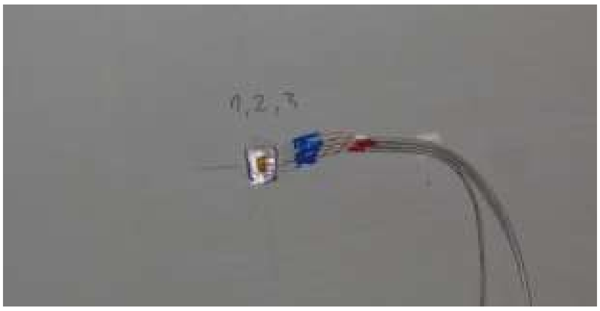


Figure 22. - Strain gauges for measuring strains at abutment U2

5.2.3 Strains at pier S6

Strains at piers, including pier S6 (Figure 23), were measured at four measurement points according to the scheme presented in Chapter 4. The labels used for the measurement points are: CGL - steel top left, CGD - steel top right, CDL - steel bottom left, CDD - steel bottom right. After analyzing the measured results, a comparison of the obtained stress values was made (Table 4).

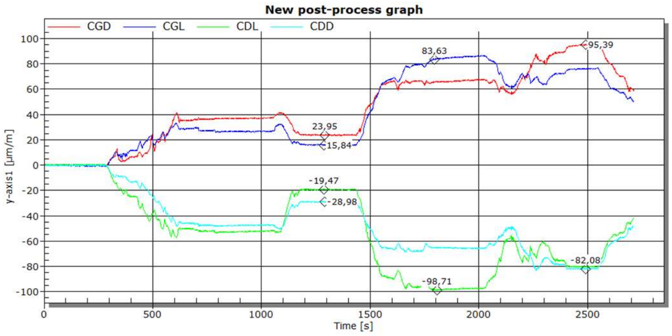


Figure 23. - Time history of strains at pier S6

Table 4. - Comparison of stresses at pier S6

	CGL	CGD	CDL	CDD
Calculated stress (MPa)	+10.35	+9.58	-29.11	-29.11
Measured stress (MPa)	+14.23	+15.00	-16.64	-11.15

5.2.4 Change in web thickness

The strains at pier S6 for the change in web thickness (Figures 24 and 25) were measured according to the scheme presented in Chapter 4 using strain gauge rosettes (Figure 26). From these, the principal stresses were calculated and then compared with the calculated results (Tables 5 and 6).

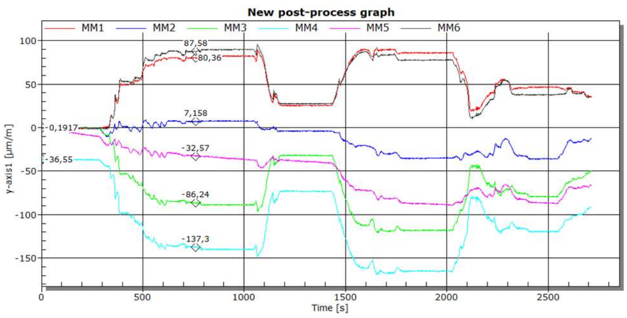


Figure 24. - Time history of strains for the change in web thickness – left

Table 5. - Comparison of principal stresses for the change in web thickness - left

	Principal stress (MPa)	"towards the pier"	"towards the span"
Calculated	σ_1	+15.74	+17.12
	σ_2	-17.43	-17.99
Measured	σ_1	+11.75	+12.8
	σ_2	-13.28	-16.31

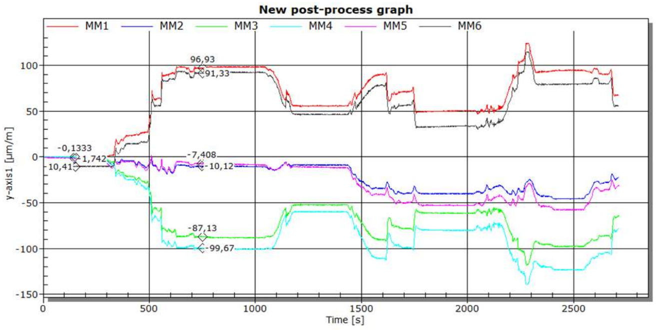


Figure 25. - Time history of strains for the change in web thickness – right

Table 6. - Comparison of principal stresses for the change in web thickness - right

	Principal stress (MPa)	"towards the pier"	"towards the span"
Calculated	σ_1	+15.59	+16.80
	σ_2	-17.11	-17.31
Measured	σ_1	+15.25	+12.98
	σ_2	-12.64	-15.11

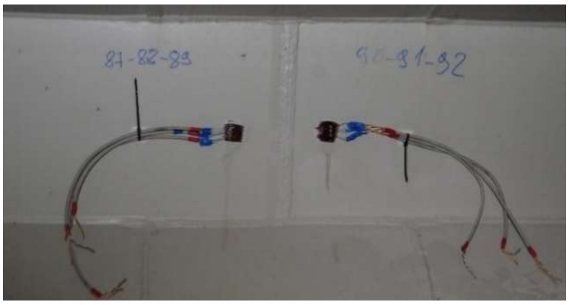


Figure 26. - Strain gauges for measuring strains for the change in web thickness

5.2.5 Change in the thickness of flanges (top) and the slab (bottom)

Strains at pier S6 at the location of the change in flange thickness (Figures 27 and 28) were measured at four measurement points according to the scheme presented in Chapter 4. The labels used for the measurement points are: MM1 - steel top left, MM2 - steel top right, MM3 - steel bottom left, MM4 - steel bottom right. After analyzing the measured results, a comparison of the obtained stress values was made (Tables 7 and 8).

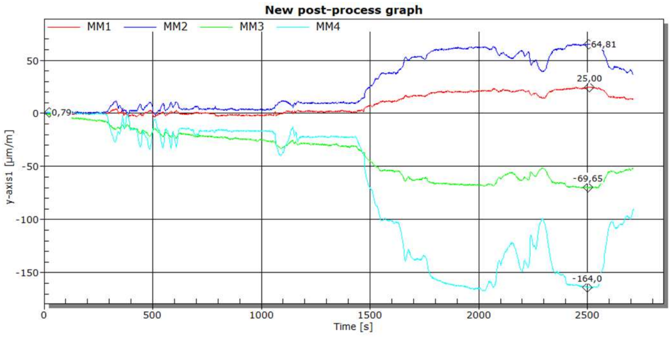


Figure 27. - Time history of strains for the change in flange and slab thickness - left

Table 7. - Comparison of stresses for the change in flange and slab thickness - left

	MM1	MM2	MM3	MM4
Calculated stress (MPa)	+8.67	+10.36	-20.59	-36.58
Measured stress (MPa)	+5.25	+13.61	-14.62	-34.44

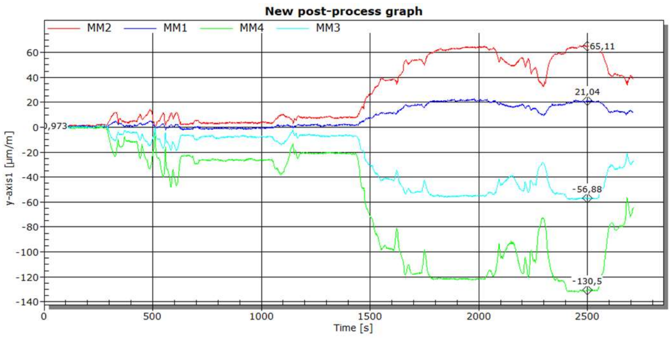


Figure 28. - Time history of strains for the change in flange and slab thickness – right

Table 8. - Comparison of stresses for the change in flange and slab thickness - right

	MM1	MM2	MM3	MM4
Calculated stress (MPa)	+8.29	+10.13	-20.61	-36.58
Measured stress (MPa)	+4.41	+13.67	-11.94	-27.40

Figure 29. - Strain gauges for measuring strains for the change in flange thickness

6. RESULTS OF DYNAMIC TESTS AND COMPARISON WITH CALCULATION

In the dynamic testing of the bridge, vertical accelerations induced by excitation with a vehicle traveling at approximately 30 km/h over a 5 cm thick wooden plank in span 4 were measured using an accelerometer (Figure 30). After processing the results, a diagram of the oscillation frequencies of the bridge was obtained (Figure 31).

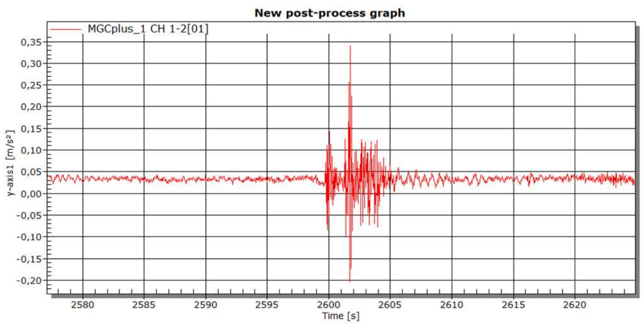


Figure 30. - Acceleration record obtained by the accelerometer

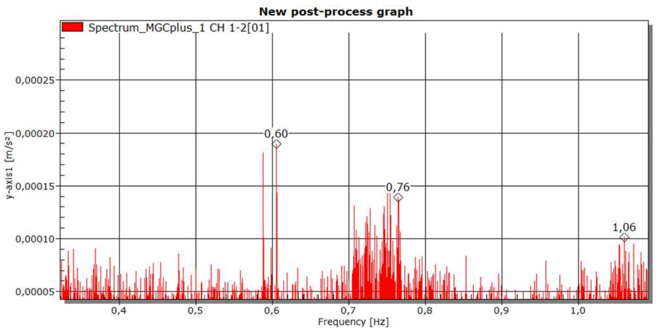


Figure 31. - Oscillation frequencies

Modal shapes of oscillation were determined using the computational model (Figure 31). The results were then processed to determine the bridge oscillation frequencies, which were compared with the calculated values (Table 9).

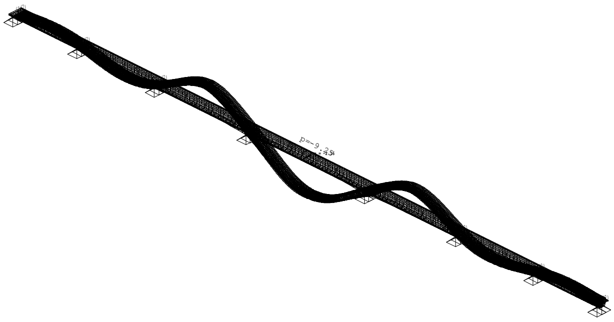


Figure 32. - First calculated modal shape of oscillation (T= 0.60 Hz)

Table 9. - Comparison of oscillation frequencies

Frequency (Hz)	Value 1	Value 2	Value 3
Calculated values	0.60	0.93	1.11
Measured values	0.60	0.76	1.06

7. CONCLUSION

To analyze the behavior of the Svilaj interstate bridge structure under static and dynamic traffic loads, load testing was performed. Load testing is conducted to verify compliance with the design, conformity of construction quality with the project requirements, and to assess the structure's ability to withstand the designed load. During the static and dynamic tests, the relevant static and dynamic parameters (displacements, stresses, and natural frequencies) were experimentally determined and compared with the corresponding calculated values. The conducted analysis of the obtained parameters, both measured and calculated, established a high level of agreement for static and dynamic effects. This suggests that the bridge performs consistently with the computational model during its service state. With this procedure, the performance of the structure was verified, which is a prerequisite for the Svilaj interstate bridge over the Sava River to be put into operation.

8. REFERENCES

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