STUDENČICA BRIDGE TESTING

Marino Jurišić
University of Mostar, Faculty of Civil Engineering, Bosnia and Herzegovina, student
Corresponding author: jurisicmarino@hotmail.com
Marko Cvitković
University of Mostar, Faculty of Civil Engineering, Bosnia and Herzegovina, student

Abstract: Studenčica bridge is located at Donji Studenci, to the southwest of Mostar in Bosnia and Herzegovina. The bridge is a great feat of engineering. It is built at a height of 88 m above the valley and is 555 m long, with main spans of 120 m. Before the bridge was opened for traffic, it was subjected to a series of tests to verify whether the construction satisfied the criteria regulated by law. Static and dynamic tests were conducted to confirm the safety of the bridge. Before the tests commenced, a numerical model of the bridge was developed and calculated by using a computer program (TOWER), and the calculation results were later compared with the measured values. The static tests comprised measurement of vertical deformation and stress in the construction, and the dynamic test involved measurement of the oscillation frequencies of the bridge. The results were analyzed to check whether the bridge performs as expected and whether it can be opened for traffic.

Keywords: construction performance, static tests, dynamic tests, result analysis, structural testing

ISPITIVANJE MOSTA STUDENČICA

Sažetak: Most Studenčica nalazi se u Donjim Studencima, jugozapadno od Mostara u Bosni i Hercegovini. Most je veliki inženjerski pothvat. Napravljen je na visini od 88 m iznad doline i dug je 555 m, s glavnim rasponima od 120 m. Prije nego što je most otvoren za promet, morao je proći niz provjera radi potvrde zadovoljava li konstrukcija uvjete propisane zakonom. Provedeni su statički i dinamički testovi da se potvrdi sigurnost mosta. Prije nego su testiranja započela, izrađen je i izračunat numerički model mosta u računalnom programu (TOWER), a rezultati su kasnije uspoređeni s izmjerenim vrijednostima. Statički testovi sastojali su se od mjerenja vertikalnih deformacija i naprezanja u konstrukciji, a dinamički testovi su mjerili frekvencije osciliranja mosta. Rezultati su analizirani radi provjere ponaša li se most prema očekivanjima i smije li se otvoriti za promet.

Ključne riječi: ponašanje konstrukcije, statički testovi, dinamički testovi, analiza rezultata, ispitivanje konstrukcija

1 INTRODUCTION

Bridge testing (numerical and load tests) is an essential part of modern bridge construction. Just like every building, a constructed bridge must be subjected to a series of tests to check whether it complies with the specific demands and requirements so it can be certified as safe and ready for use. Unfortunately, throughout history, some constructions have collapsed; such accidents provide an insight into problems and help researchers learn from past mistakes. Modern technology provides the means to prevent such mistakes and confirm the safety and stability of a construction before it is put to use. The methods and sequences of the tests and interpretation of the test results are determined by the standards that are precisely regulated by law in every country or region (in this case, “Pravilnik za ispitivanje mostova probnim opterećenjem,” the current standards in Bosnia and Herzegovina) [1]. Different equipment is used to measure different factors that are compared to the results obtained while testing. As such, it is possible to assess whether the construction is performing as expected. Before the tests commence, the material (concrete, steel) is investigated to confirm that the properties of the material are as described in the project. In this study, bridge samples of built-in concrete and steel were tested in the laboratory, and concrete quality was determined by static tests. This paper describes certain ways of bridge testing that were employed for the Trebižat and Studenčica bridges and provides an interpretation of the results. These bridges are located to the southwest of Mostar in Bosnia and Herzegovina and are named after the rivers that flow under them. The Faculty of Civil Engineering, University of Mostar, tested these bridges with different equipment commonly used for bridge testing. Since similar procedures were used for both bridges, only Studenčica (longer bridge) is reviewed in this paper, considering that the same applies to the other bridge.

2 CHARACTERISTICS OF STUDENČICA BRIDGE

The bridge is located at Donji Studenci and is a part of highway corridor Vc, section Počitelj, along the border of the Republic of Croatia. It spans over the Studenčica river and is built at a height of 88 m. The bridge supports a full highway profile, and therefore, it was designed as a dual construction where each one served for a different highway direction. The highway profile (one direction) consists of two lanes 3.75 m wide, one emergency lane 2.5 m wide, and a protective strip of pavement 0.5 m wide. The Jersey barrier is 0.46 m wide. Thus, the complete width of one bridge is 0.46 + 0.50 + 2.50 + 2*3.75 + 2*0.50 + 0.46 = 12.42 m. The bridge has six spans of lengths 70, 120, 120, 120, 80, and 45 m, and thus, its complete length is 555 m. The static system is a frame that consists of a horizontal girder and vertical piers. The cross section of the girder is a box made of pre-stressed concrete. The quality of the concrete is C40/50 (C50/60) with B 500B reinforcement bars and Y 1860 S7 pre-stressing steel. The cross section of the girder box varies; over the abutment and in the middle of the spans, the bridge is 3.1 m high, and over the piers, it is 6.5 m high. The main part of the bridge was built using a balanced cantilever construction method; however, the spans closest to the abutments were built on a scaffolding [2].
Figure 1 is presenting Studenčica bridge under construction and completed bridge.

Figure 1 Bridge under construction and completed bridge

3 STANDARDS AND REGULATIONS USED IN TESTING

Testing was conducted in accordance with “Pravilnik za ispitivanje mostova probnim opterećenjem” (“Standards for test load bridge testing”) [3]. These regulations require that every road bridge with a span greater than 15 m be subjected to both static and dynamic test loads. They also require that the test load should be between 0.5 and 1.0 of the load used for designing the bridge (coefficient U) [3]. In this case, the test load was four to six vehicles placed according to the calculation such that they had the biggest impact on the bridge. The deformations and stress in the bridge were calculated before the test, and the measured results should be lesser than the calculated ones. Stress diagrams were plotted for the characteristic cross sections where the strains were measured. The frequency in the vertical direction was also measured. Calculation was conducted using Tower 7 Radimpex Beograd program [4].

4 TESTS AND RESULTS

As stated earlier, the bridge has to be confirmed safe before it is put to use. For a bridge to be declared safe, it should pass the static and dynamic tests conducted by the authorized personnel. The ability of the bridge to withstand certain (predicted) amounts of load with acceptable deformations is demonstrated through these tests [5]. The results are interpreted by competent engineers; based on the quality of the results, the engineers determine whether the bridge satisfies the criteria set up at the beginning of the testing.

4.1 Static tests

Static tests of the bridge are conducted by applying load on bridge spans and above piers to cause deformations and stresses in the construction. In the present case, the load was six trucks weighing 30–50 tons. The weight of the trucks was distributed on their axles and was used as such in the calculation. Appropriate positioning of the trucks on the bridge (Figures 2, 3 and 4) resulted in the desired stress and deformation in the construction, and different positions were used to test the three spans and two piers. The test load was 56% of the live load (coefficient U = 0.56).

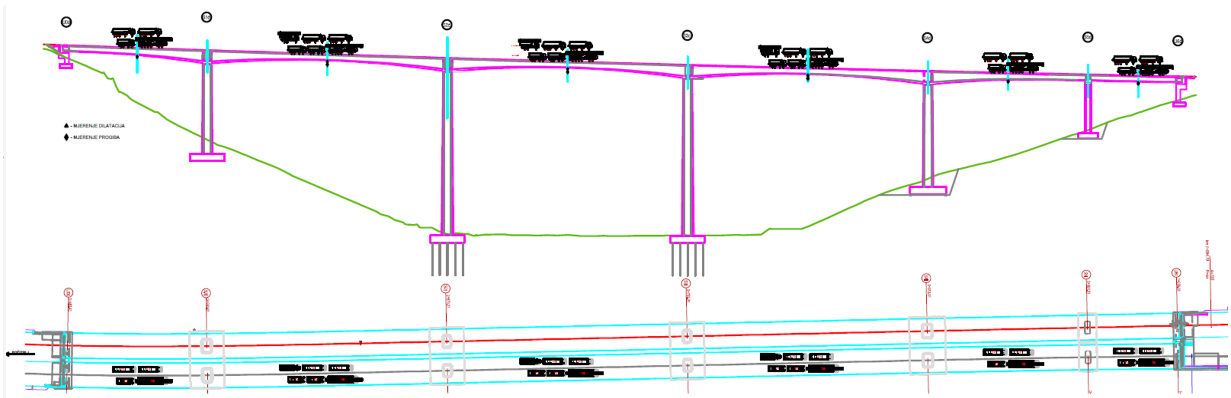

Figure 2 Illustration of span testing [6]

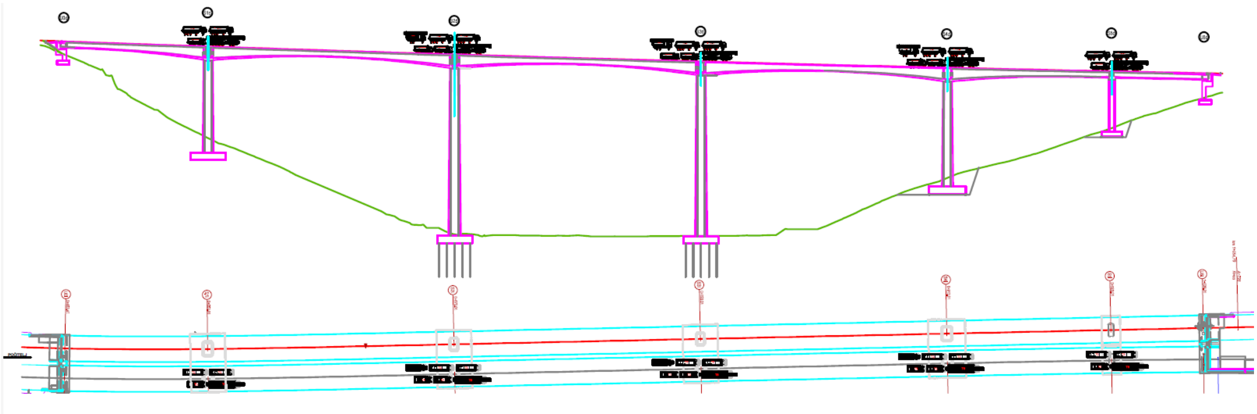

Figure 3 Illustration of pier testing [6]

Figure 4 Test load on the bridge [6]

S 1

fck	64,89	57,64	61,98	58,23	54,56	53,81	54,31	60,56	54,56	62,23	59,98	59,64		62,56	59,98	60,73	55,39	60,31	54,39	53,81	54,56	51,56	61,23	56,64	58,14
U0L-XII10L	SPOJNI	XI10L	X10L	IX10L	VIII10L	VII10L	VI10L	V10L	IV10L	III10L	II10L	I10L	BAZNI	I12L	II12L	III12L	IV12L	V12L	VI12L	VII12L	VIII12L	IX12L	X12L	XI12L	SPOJNI
G.P. 77,90													G.P. 67,60												
REBRA 71,11	77,9	69,2	74,4	69,9	65,5	64,6	65,2	72,7	65,5	74,7	72	71,6	REBRA 61	75,1	72	72,9	66,5	72,4	65,3	64,6	65,5	61,9	73,5	68	69,8
D.P. 71,11													D.P. 75,30												
48,44 Mpa												1	64,3		53,56										
58,4 Mpa												2	66,7		55,56										
												3	68,4		56,98										
												4	62,7		52,23										
												5	58,1		48,4										
												6	61,6		51,31										
												7	67,3		56,06										
												8	65,8		54,81										
												9	56		46,65										
													53 Mpa												
													52,9 Mpa		fck										

Figure 5 Built-in concrete strength [6]

The rest of the bridge has similar concrete strengths; therefore, in the model, the quality of pier concrete was C40/50 and that of span concrete was C50/60 (Figure 5).

Vertical deformation of the bridge was measured at every span by using geodetic instruments with an accuracy of ½ mm [6]. The regulations state that no additional load may be on the bridge and no works can be performed while the vertical deformations are being determined because in such situations, the results may be affected causing false readings [3]. The position of every truck was controlled, and hence, the possible locations of maximum deformations were known. With these measures, it was possible to check whether the construction underwent any plastic deformations. The absence of plastic deformations indicated that the bridge remained in the elastic state (stress and strain were proportional) and that the stress could be calculated if the Young's modulus for concrete and relative longitudinal deformation were known [7]. Table 1 lists the vertical deformations during and after the load was applied. The piers did not undergo any longitudinal deformations, and every deformation that existed in the middle of the spans when the bridge was loaded disappeared when the load was removed; this means that every span returned to its original position with no plastic deformation.

Table 1 Geodetic measurements [6]

Measured points	A (starting state) (m)	B (loaded state) (m)	A-B (m)	C (unloaded state) (m)	A-C (m)
U0					
1/2	105.896	105.888	-0.008	105.896	0.00
S1	104.708	104.708	0.00	104.708	0.00
1/2	1.343	1.363	-0.020	1.343	0.00
S2	3.278	3.278	0.00	3.278	0.00
1/2	1.450	1.475	-0.025	1.450	0.00
S3	3.163	3.163	0.00	3.163	0.00
1/2	1.569	1.591	-0.022	1.569	0.00
S4	3.084	3.084	0.00	3.084	0.00
1/2	106.886	106.877	-0.009	106.886	0.00
S5	105.985	105.985	0.00	105.985	0.00
1/2	106.190	106.185	-0.005	106.190	0.00
U6					

Relative deformation of the concrete was measured at four locations in the cross section, and it was controlled within the second, third, and fourth span and also above S2 and S3 piers. For this test, electrical strain gages, namely, HBM type K-LY41 100/120, were used [8]. These strain gages can determine the strain in the concrete by measuring the electrical resistance before and after load is applied. Here, the bridge was assumed to be elastic under the test load; this assumption was verified by using the geodetic measurements. This is very important because if the concrete is elastic, its stresses can be easily calculated. In each cross section of the bridge, four strain gages were connected (Figure 6) to the central MGC plus system where the strain data were collected using the Catman AP program package [8]. The system run time was sufficient for observing the starting state, loaded state, and the unloaded state, and it was controlled by the personnel testing the bridge. The software then plotted a diagram showing the strain in the concrete in the given time period (Figures 7 and 8). Results of stress and strain measurement are presented in Tables 2 and 3.

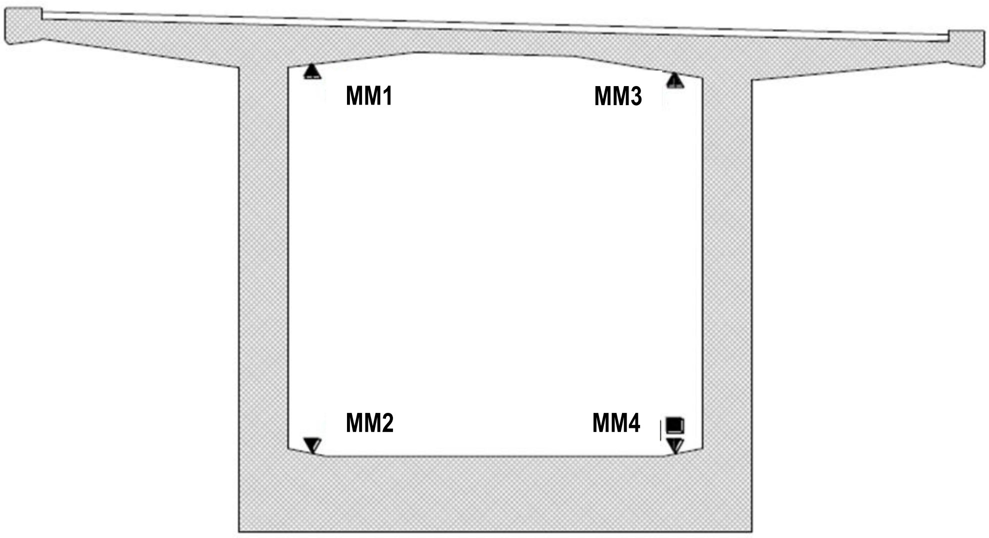

Figure 6 Position of strain gages [6]

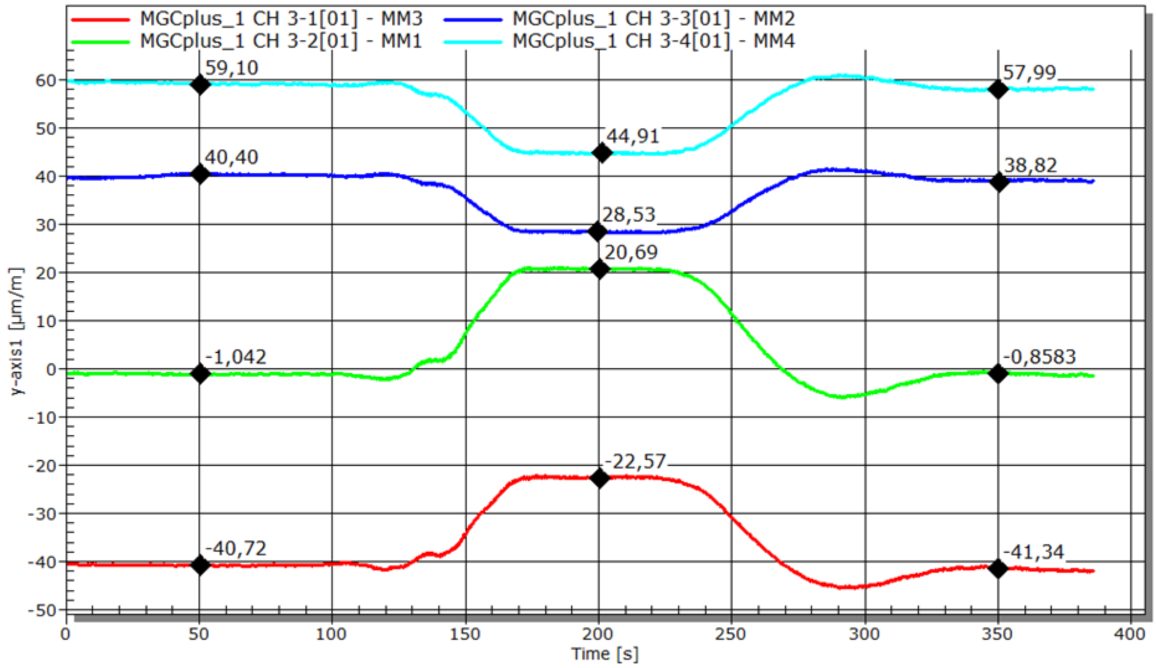

Figure 7 Example of strain diagram for the region over a pier (S3) in Catman AP [6]

Table 2 Strain and stress over a pier (S3) [6]

	Strain MM1 (µm/m)	Strain MM2 (µm/m)	Strain MM3 (µm/m)	Strain MM4 (µm/m)
Starting state	-1.04	40.40	-40.72	59.10
Loaded state	20.69	28.53	-22.57	44.91
Unloaded state	-0.85	38,82	-41.34	57.99
Strain	+21.73 µm/m	-11.87 µm/m	+18.15 µm/m	-14.19 µm/m
Stress	+0.82 MPa	-0.45 MPa	+0.68 MPa	-0.53 MPa

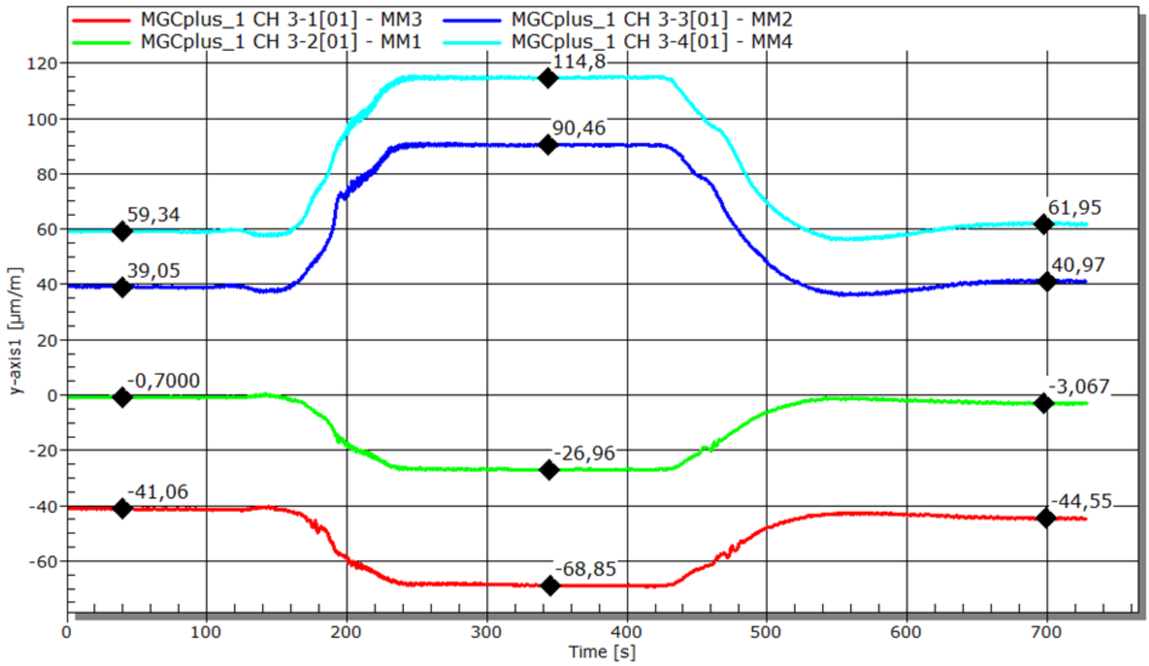

Figure 8 Example of a strain diagram (third span) in Catman AP [6]

Table 3 Strain and stress over the third span [6]

	Strain MM1 (μm/m)	Strain MM2 (μm/m)	Strain MM3 (μm/m)	Strain MM4 (μm/m)
Starting state	-0.07	39.05	-41.06	59.34
Loaded state	-26.96	90.46	-68.85	114.80
Unloaded state	-3.06	40.97	-44.55	61.95
Strain	-26.89 μm/m	+51.41 μm/m	-27.79 μm/m	+55.46 μm/m
Stress	-1.02 MPa	+1.95 MPa	-1.05 MPa	+2.10 MPa

4.2 Dynamic test

Dynamic testing of a construction involves measuring the oscillations of the bridge under dynamic load [5]. The dynamic load is actually the force applied on the bridge when a truck moving at a certain speed goes over a plank. It has an impact on the construction, thus triggering oscillations. The acceleration resulting from such impacts, as in the case of earthquakes, can be measured to plot a graph for the duration when the dynamic force was applied. In this test, T3 truck passed over a 5-cm-thick board at a speed of 40 km/h. The test was conducted only on the central (third) span. The accelerations were measured by HBM acceleration transducers, type B12/500, and the data were collected by the MGC plus system [6]. Frequency diagrams were plotted using the obtained accelerations (Figure 9).

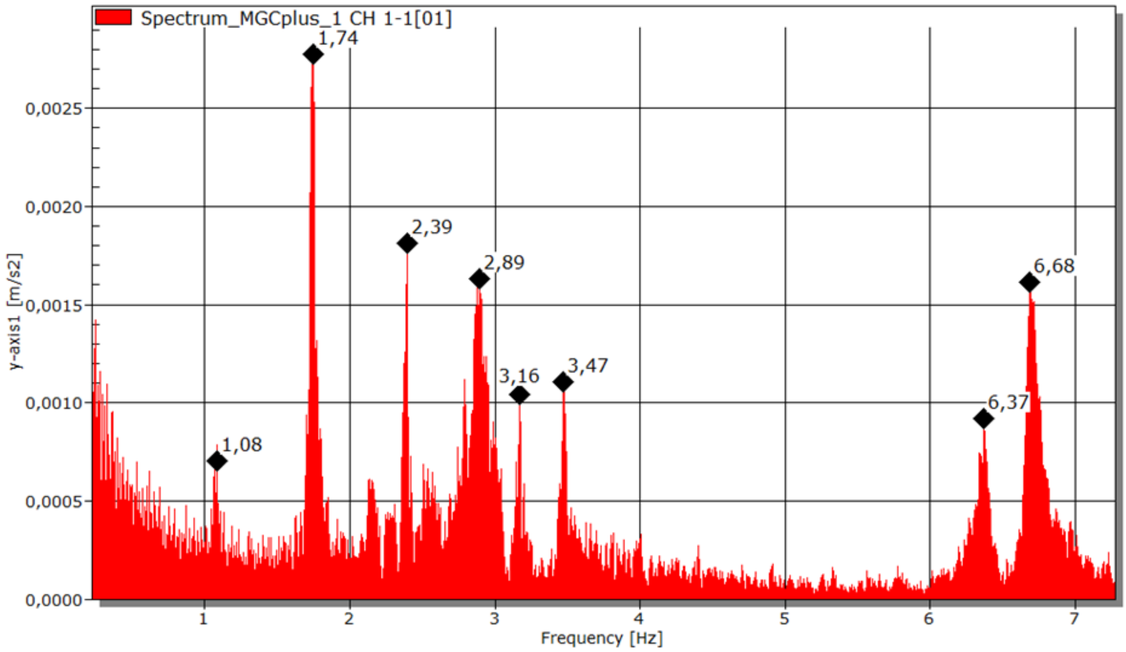

Figure 9 Frequency diagram [6]

5 COMPARISON OF MEASUREMENT RESULTS WITH MODEL CALCULATIONS

In order to confirm that the bridge is safe and ready for use, it must be proved that the bridge endured the static and dynamic load as predicted. For this purpose, the measured values are compared with the calculated ones (Table 4). For the static test, the geodetic measurements after and before the load was applied should be the same. It is also very important that the readings above the piers remain constant because this is an indicator of foundation settling (piers have great longitudinal stiffness; hence, the piers are considered rigid bodies, and this means that any readings above the piers while the load is applied indicate foundation settling). The stresses measured by the stress gages should be close to our calculated values because the material had elastic properties (Table 5). Concrete strength was investigated in situ. In the dynamic load test, the frequencies measured on the bridge should be close to the calculated values for the dynamic model of the bridge (Table 6). During the tests, the bridge should also be checked visually for cracks to confirm the quality of the material used.

Table 4 Comparison of measured and calculated vertical deformations [6]

Measured points	A (calculated values) (mm)	B (measured values) (mm)	Relative error	A-B (mm)
U0				
1/2	-8	-7	0.125	-1
S1	0	0	0	0
1/2	-20	-22	0.1	2
S2	0	0	0	0
1/2	-25	-24	0.04	-1
S3	0	0	0	0
1/2	-22	-22	0	0
S4	0	0	0	0
1/2	-9	-11	0.22	2
S5	0	0	0	0
1/2	-5	-4	0.2	-1
U6				

Table 5 Comparison of controlled and calculated stress [6]

		Calculated stress (MPa)	Controlled stress (MPa)	Relative error	Difference (MPa)
Second span	MM1	-1.08	-0.80	0.259	-0.28
	MM2	2.29	+1.87	0.183	0.42
	MM3	-1.08	-0.94	0.130	-0.14
	MM4	2.28	+2.10	-0.079	-0.18
Second pier	MM1	0.81	+0,71	0.123	0.10
	MM2	-1.06	-0.53	0.500	-0.53
	MM3	0.84	+0.67	0.202	0.17
	MM4	-1.10	-0.54	0.418	-0.46
Third span	MM1	-1.06	-1.02	0.038	-0.04
	MM2	2.35	+1.95	0.170	0.40
	MM3	-1.05	-1.05	0.000	-0.00
	MM4	2.36	+2.10	0.110	0.26
Third pier	MM1	0.88	+0.82	0.068	0.06
	MM2	-1.10	-0.45	0.591	-0.65
	MM3	0.89	+0.68	0.236	0.21
	MM4	-1.02	-0.53	0.480	-0.49
Fourth span	MM1	-1.05	-1.03	0.019	-0.02
	MM2	2.23	-	-	-
	MM3	-1.05	-0.93	0.124	-0.13
	MM4	2.23	+2.15	0.036	0.08

Table 6 Comparison of calculated and measured frequencies [6]

Frequency	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6	Value 7
Calculated values (Hz)	1.16	1.78	2.17	2.47	3.12	3.64	3.99
Measured values (Hz)	1.08	1.74	2.39	2.89	3.16	3.47	6.68
Difference (Hz)	0.08	0.04	-0.22	-0.47	-0.04	0.17	-2.69

6 CONCLUSION

In conclusion, Studenčica was a very challenging construction project. It is the highest bridge in Bosnia and Herzegovina. The tests showed that the designers and builders completed their task successfully. The vertical deformation measurement showed that the bridge is performing as expected and that its vertical deformations are close to the model calculations. Plastic vertical deformations are nonexistent, and thus, the regulations (plastic vertical deformations for pre-stressed constructions should not exceed 20% of the measured ones when the load is removed) are satisfied [3]. All deformations disappeared once the load was removed; in other words, the construction exhibits elastic properties. In addition, there were no deformations (measurements) on the piers; this implies that there was no differential settling of the foundation. Stresses in the construction were measured indirectly over the strain because the material retained its elastic properties. The stress in the construction was always lesser than the calculated values, thus meeting the criteria [3]. Some bigger deviations were allowed for concrete on the safety side because it is a non-homogeneous material. Visual inspection proved that there were no cracks in the bridge; this implies that the pre-stressing was done successfully and that enough compressive force was applied to the construction. The dynamic tests showed that the measured oscillation frequencies are very similar to the calculated ones and that the bridge performed as expected. All tests showed that the construction satisfied the criteria set as per the regulations and that the bridge can be opened for traffic. The bridge is now in operation, and it carries the Vc highway corridor towards the border with Croatia, connecting Bosnia and Herzegovina with the European highway network.

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