



EKSPERIMENTALNA ISPITIVANJA SKALIRANOG MODELA I SEGMENTA LUKA STAROG MOSTA U MOSTARU

Prethodno priopćenje/Preliminary communication

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Sažetak: Zidani lučni mostovi zbog svojega karakterističnog izgleda i kompleksnosti materijala od kojih su građeni i danas su predmet eksperimentalnih i numeričkih analiza. Jedan od istaknutih primjera ovog tipa konstrukcija jeste i Stari most u Mostaru, koji je, zajedno s lokalitetom mosta, pod zaštitom UNESCO od 2005. godine. Upravo je ovaj simbol grada na Neretvi odabran kao osnova za analizu ponašanja zidanih lučnih mostova i njihovih elemenata. Kroz rad će biti prikazani rezultati kvazistatičkih ispitivanja elemenata veze provedenih na modelima segmenata svoda Starog mosta u razmjeri 1:3 kao i rezultati ispitivanja ponašanja fizičkog modela Starog mosta skaliranog u razmjeri 1:9 ispitivanog na seizmičkoj platformi za različite nivoe seizmičke pobude. Modeli su izgrađeni s realnom aplikacijom veza između kamenih elemenata - klamfe, trnovi i tekuće olovo. Utvrđivanje kapaciteta nosivosti i načina popuštanja elemenata veza ispitivanih segmenata te određivanje mehanizma loma modela mosta osnovne su zadaće provedenih eksperimentalnih istraživanja.

Ključne riječi: zidani lučni mostovi, statičko opterećenje, seizmičko opterećenje, elementi veze, kapacitet nosivosti, razvoj pukotina, mehanizam loma.

EXPERIMENTAL TESTING OF SCALED MODEL AND ARCH SEGMENTS OF THE OLD BRIDGE IN MOSTAR

Abstract: Due to their characteristic appearance and complexity of materials used for their construction, masonry arch bridges are still the subject of experimental and numerical analyses. One of the characteristic examples of this type of structures is the Old Bridge in Mostar that, along with the bridge location, has been under UNESCO protection since 2005. It is exactly this symbol of the town residing on the Neretva River that has been selected as the basis for analysis of behavior of masonry arch bridges and their structural elements. This paper will present the results of the quasi-static tests on connection elements carried out on models of arch segments of the Old Bridge at the scale of 1: 3 as well as the results of the shaking table tests of the behavior of the physical model of the Old Bridge scaled to 1:9 under different levels of seismic excitation. The models were built by application of real connection elements between stone elements – cramps, dowels and liquid lead. Definition of bearing capacity and mode of deterioration of the connection elements of the tested segments as well as definition of the failure mechanisms of the bridge model are the main tasks of the performed experimental investigations.

Key words: masonry arch bridges, static load, seismic load, connection elements, bearing capacity, development of cracks, failure mechanism.



1. DESCRIPTION OF THE CONDUCTED RESEARCH

Knowing the behavior of masonry structures subjected to earthquakes is of primary importance in seismically active areas. Destructive damage to masonry structures caused by earthquakes in the last decades prompted engineers to more carefully consider masonry as a construction material, to identify its disadvantages and to find ways to overcome them, and thereby reduce the damage of destructive earthquakes as much as possible.

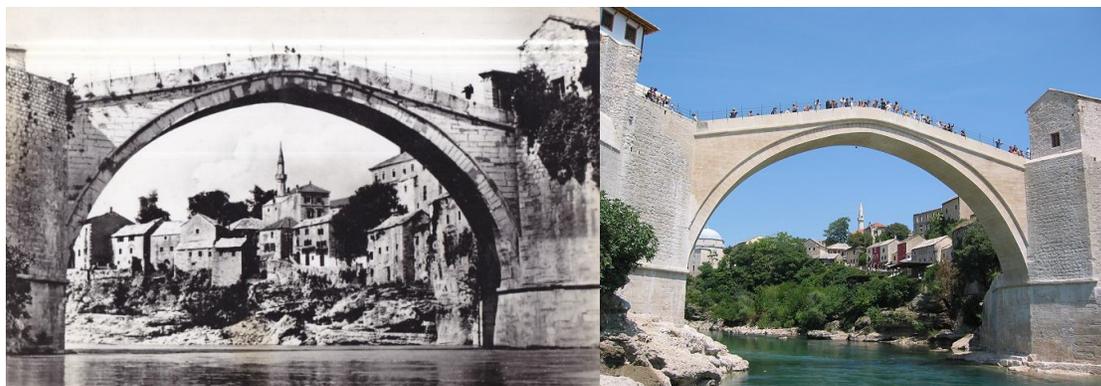
Experimental tests divided into two stages should provide results in the form of displacements, accelerations, deformations, and all other quantities of interest to assess the seismic stability of arch bridges constructed with stone walls. The laboratory tests were conducted at the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), University of Sts. Cyril and Methodius in Skopje, the Republic of Macedonia.

In the first stage of experimental research, six arch segments at scale 1:3 were constructed and tested in the laboratory under quasi-static conditions. This stage of research was aimed at establishing the bearing capacity of connection elements subjected to possible loads occurring in the vault of the bearing arch and the mode of failure of this connection and activation of connection elements.

In the second stage, a model of the Old Bridge at scale of 1:9 was built and tested on the shaking table at different load levels. This stage of research was aimed at establishing the failure mechanism of the Old Bridge model, with measurements of all quantities of interest for further analyses.

2. MOSTAR AND ITS BRIDGE

The Mostar area has been inhabited since the earliest history, which is borne out by numerous archaeological finds from the Neolithic to the late Middle Ages. What particularly attracts attention is the settlements typical of the Bronze Age and Iron Age - hill-forts and stone grave mounds - tumuli, as well as remains of settlements from various epochs. As written in the book *Old Bridges in Bosnia and Herzegovina*, the first reference of the present-day Mostar site was made in 1452 in the Dubrovnik archive under the name "duo castelli al ponte de Neretva". According to available archaeological data and historical records, wooden bridges built in the mid-15th century existed exactly at the site of the present-day Old Bridge, before construction of the Old Bridge. With the arrival of the Ottoman Empire and increased need for transport through this site and the growing need for safer crossing of Neretva, Turkish Sultan Suleiman the Magnificent ordered construction of a new stone bridge. The bridge is the work of the architect Mimar Hajrudin, a student of Mimar Sinan, the greatest Turkish architect. It was built in 1566.



a) b)
Figure 1. The Old Bridge and the reconstructed "new" Old Bridge



Although over the centuries the bridge (Figure 1.-a) was exposed to various influences, both to elements and its very use, more serious repair measures or similar interventions were not recorded in archives until 1952, when an inspection established that it was necessary to carry out repair of the worn-out wooden floor structure on bridge towers. Also, it was proposed to remove vegetation from the bridge walls, which was the cause of the occurrence of cracks on them. In the period from 1954 to 1957, the bridge foundations and the river banks were rehabilitated. In 1963, by then the most comprehensive bridge repair was carried out by grouting the bridge arch and replacing damaged stone blocks. In addition to archaeological explorations of the site, detailed photogrammetric survey of the entire structure was carried out in 1982. The Old Bridge was demolished in 1993, and after the reconstruction which was completed in 2004 (Figure 1.-b), the new Old Bridge was registered in the UNESCO List of Protected Cultural Monuments.

The main structural element of the bridge is the load-bearing arch with the northern span of 28.71m and the southern span of 28.62m. The arch stone is 40x80x100cm in size. On the average, the thickness of the arch is 80 cm and its width is 395 cm. The great span and characteristics of the material required introduction of the central rib between the spandrel walls of the bridge in order to influence the bridge weight. Other elements are the bridge abutments, wing walls, spandrel stone walls defining the bridge face, bridge cobblestone paving, bridge parapets, end cornice and wrought iron railings, subsequently installed on existing stone parapets.

Stone elements of the bridge were reinforced by using fixings hand-made of wrought iron and placed over connecting joints. These iron connectors, or cramps and dowels, were essentially applied on stone elements with purposely carved slots with slightly wider bottom to avoid making it completely airtight. The connectors also had wider edges, and after they were fixed, liquid lead was poured into the slots to complete the assembly (Figure 2).



Figure 2. Details of bridge arch assembling

Archaeological explorations proved the previously described assumptions on the wooden bridges that preceded the Old Bridge. Remains in the form of connecting wedges as well as support points of nine vertically placed oak beams, laid in three rows, projected to the river as brackets, were found on both sides. Archaeological explorations also confirmed earlier age of the towers, which had been part of the medieval fortification system before the stone bridge was constructed.

3. THE FIRST STAGE OF EXPERIMENTAL RESEARCH

The connections used when assembling stone elements of the bridge arch, as said in the previous chapter, are cramps and dowels made of wrought iron with additional use of liquid lead. The assembly technique using the aforementioned connection elements, along with the use of mortar, allowed an efficient linking system that was widely applied during construction of the Old Bridge in Mostar.

The first stage of laboratory testing involves construction of six arch segments at scale



1:3 and their quasi-static testing in the laboratory. The geometry of arch segments produced in accordance with the adopted scale is shown in Figure 3. The aim of this stage of research was to establish the bearing capacity of all connection elements subjected to possible loads occurring in the vault of the bearing arch, as well as the way in which the loss of connection and bearing capacity occurs in stone masonry.

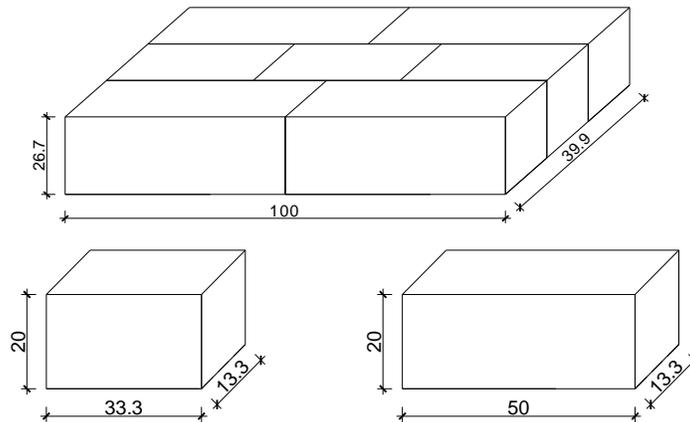


Figure 3. Dimensions of test segments

The produced arch segments are a true replica of the arch segments of the Old Bridge in Mostar, and the characteristics of the materials of stone blocks, mortar and connection elements used for construction of the segments are approximately the same as of the materials used for construction of the Old Bridge.



Figure 4. Produced arch segment models

The prepared segments, shown in Figure 4, were examined by testing two sets at a time with the same load application principle in order to determine their load-bearing capacity under the given load. Depending on the position of the tested element, the results were obtained that describe the behavior under bending load for two different ways of orientation of the tested elements and the behavior during shear loading. Figure 5 shows how test segments were set in the testing position.



Figure 5. Constructed masonry segments placed in position for testing

3.1. Testing of produced segments and results

Testing of the produced segments was conducted by semi-cyclic loading, while recording the values of force and its corresponding displacement.

The following figures show the force-displacement graphs for segments tested for bending - type 1 (Figure 6), bending - type 2 (Figure 7) and shear (Figure 8). The force-displacement graphs obtained for other tested segments have a similar form.

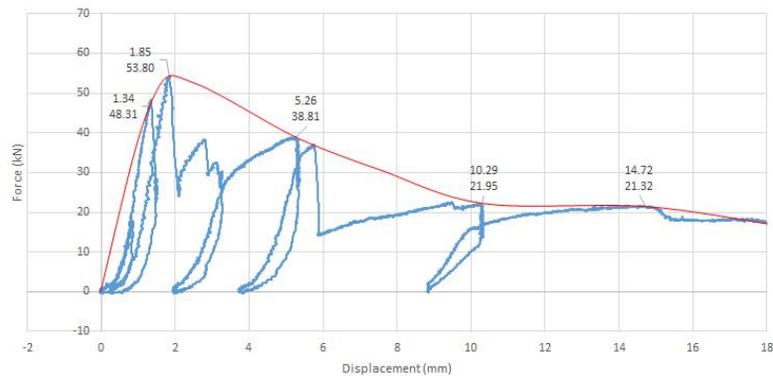


Figure 6. The force-displacement graph of the tested segment E1-1-B-V

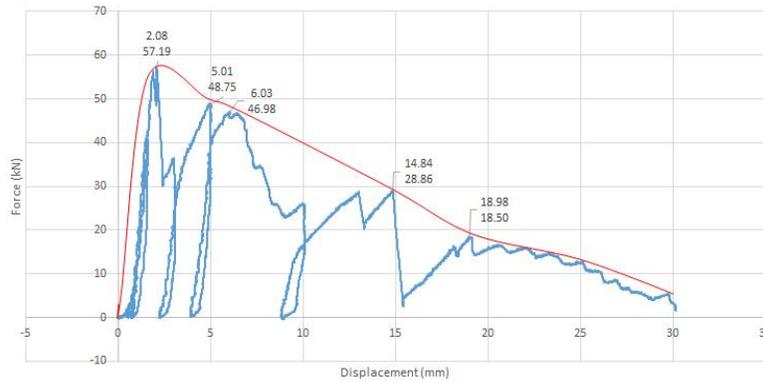


Figure 7. The force-displacement graph of the tested segment E2-1-B-L

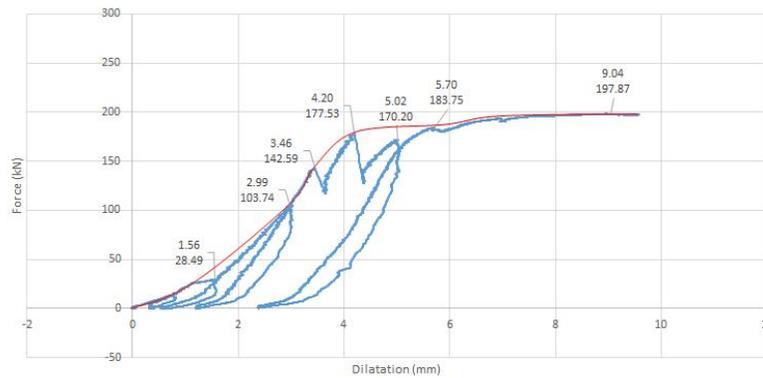


Figure 8. The force-displacement graph of the tested segment E3-1-S

Measured displacement values for the applied load are shown in Table 1 for all tested segments.

E1-1-B-V	Force (kN)	48.31	53.80	38.81	21.95	21.32
	Displacement (mm)	1.34	1.85	5.26	10.29	14.72
E1-2-B-V	Force (kN)	34.84	48.48	49.42	37.62	35.62
	Displacement (mm)	1.23	3.69	4.66	9.91	19.87
E2-1-B-L	Force (kN)	57.19	48.75	46.98	28.65	18.50
	Displacement (mm)	2.08	5.01	6.03	13.03	18.98
E2-2-B-L	Force (kN)	69.84	59.55	15.94	9.27	
	Displacement (mm)	1.88	7.40	10.13	18.25	
E3-1-S	Force (kN)	28.49	103.74	142.59	183.75	197.87
	Displacement (mm)	1.56	2.99	3.46	5.70	9.04
E3-2-S	Force (kN)	149.63	204.62	223.63	244.23	
	Displacement (mm)	2.89	3.93	4.46	5.53	

Table 1. Measured displacement values



By examining the measured displacement values for the tested segments, it can be concluded that the bearing capacity of the segments tested for shear is up to three times larger than the bearing capacity of the segments tested for bending. Participation of connection elements and their numbers and activation mode dependent on the applied load directly influence the obtained results.

The loss of bearing capacity of the tested mortar segments for the initial loading stage was accompanied by the appearance of the first cracks (Figure 9) in mortar joints, which was registered by maximum applied force on the force-displacement graphs shown above.



Figure 9. Occurrence of the first cracks in mortar joints

Further loading is taken by connecting elements, or cramps and dowels. Failure of these connections causes gradual reduction of bearing capacity of the tested elements and the mechanism is manifested in pulling out of cramps from their seats sealed by liquid lead, followed by pulling out of dowels from their seats (Figure 10).



Figure 10. Cramps and dowels pulling out from their seats

The tests showed the occurrence of cracks and failure of stone elements, but for the very final load application stage, when a complete failure of the tested segments occurred. Breaking of steel connection elements, or cramps and dowels, was not observed for the conducted tests.



4. THE SECOND STAGE OF EXPERIMENTAL RESEARCH

Arch structures take an important place in historic structures and are one of the most visually impressive forms conceived by human mind. Masonry arch bridges still provide free flow of goods and services and draw attention with their appearance and durability, but also require special attention in order to continue to serve their purpose. To analyze the behavior of masonry arch bridges, it is essential to know the behavior of the bridge's load-bearing vault. Elements of which load-bearing vaults of arch masonry bridges are built are stone blocks, which have high compressive strength and negligible tensile strength, and mortar, whose bearing capacity cannot be counted on in seismic conditions and whose basic task is to fill joints between stone blocks. In addition to these two basic elements in the structure, we also witness structural connection elements such as cramps, dowels and liquid lead. From all of the above we can see that masonry arch structures are very complex and require special attention in analysis.

In the second stage of experimental research, attention was focused on the global behavior of masonry arch structures in order to obtain a realistic picture of the efficiency of stone masonry connections and the way of failure of the load-bearing arch of the structure under intense vibration conditions. For the purpose of this stage of research, a model of the Old Bridge in Mostar was made at scale 1:9 (Figure 11) with all connection details, which was tested on the shaking table of the Institute of Earthquake Engineering and Engineering Seismology in Skopje for different load levels up to failure of the structure.

The aim of model testing on the shaking table is to investigate seismic behavior up to failure of the model, with monitoring of all structural response quantities - displacements, accelerations, deformations, which are of importance for assessing the global seismic stability and the way in which the failure mechanism develops, or the effect of connections in preserving structural integrity. The testing was conducted in several stages:

- defining the dynamic characteristics of the model;
- testing in the linear domain with a series of lower-intensity seismic tests;
- tests up to failure, with intense excitations, with occasional checking of dynamic properties and decrease in model stiffness.



Figure 11. The model of Old Bridge at scale 1:9



The bridge model made for the second-stage experimental research was constructed as gravity force neglected model, using the materials for stone, mortar and steel connection elements of the same or sufficiently similar characteristics as in the original structure. The selected scale is conditioned by the dimensions of the shaking table – 5.0x5.0 m. Consistent with this, the total length of the tested model along with the foundation structure is 3.76m, the span of the bridge model arch is 3.16m, and the height of the model arch from the foundation to the lower point of the arch is 1.33m. The geometry according to which the bridge model was built is shown in Figure 12.

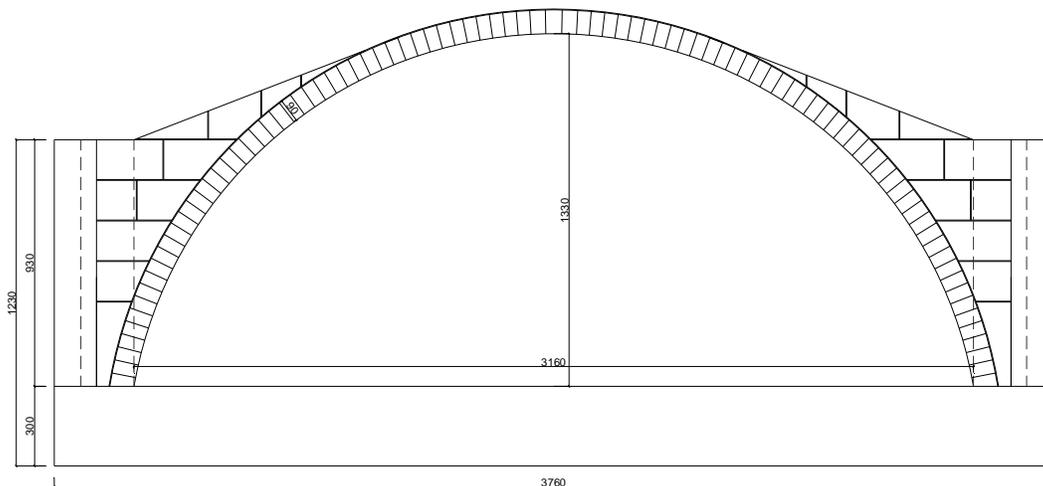


Figure 12. Bridge model geometry

Preparation of the model for testing was carried out so as to include as many measurement points on the model as possible, primarily the points near the arch top and the third points of the arch. In addition to the above listed, instruments also cover points near and on the foundation structure. The testing program specifies 17 acceleration measurement

points, 11 relative displacement measurement points, and 3 absolute displacement measurement points of the bridge model (Figure 13), a total of 31 measurement point.

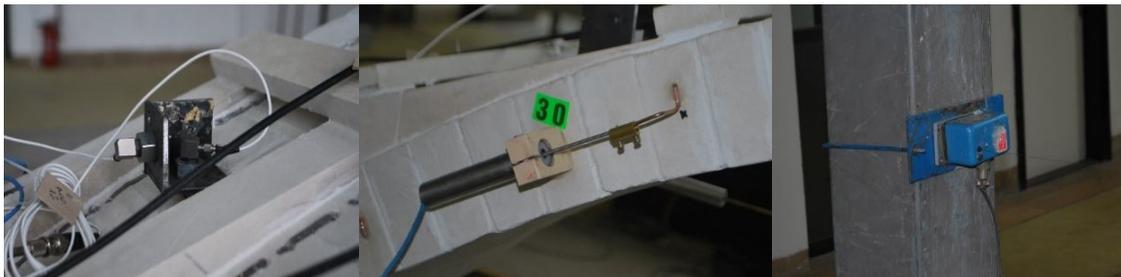


Figure 13. Accelerometer, relative and absolute displacement transducer

Accelerometers, which measured structural response in the horizontal (longitudinal bridge direction) and vertical direction, were installed as structure acceleration meters. LVDT sensors (Linear Variable Differential Transformers) were installed as structural relative displacement meters, which measured relative displacements of the arch structure or relative displacements between stone elements. LP sensors were installed on the reference pole as



structure absolute displacements meters and they measured absolute displacements of the structure.

4.1. Bridge model testing and results

For seismic testing of the Old Bridge model, it was adopted to apply the accelerogram of the Petrovac earthquake from 15 April 1979, which is scaled by the factors 1:9, 1:6 and 1:3 for the purposes of bridge model testing or for excitation of bridge model vibrations in the resonant state. The excitation was applied simultaneously in the longitudinal (Y) and vertical (Z) directions.

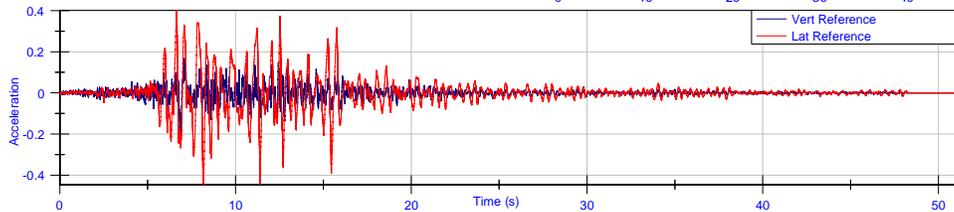


Figure 14. TH for Petrovac, SF 1:1

The scaled accelerograms of the Petrovac earthquake used for the dynamic testing of the Old Bridge model are shown on the following figures:

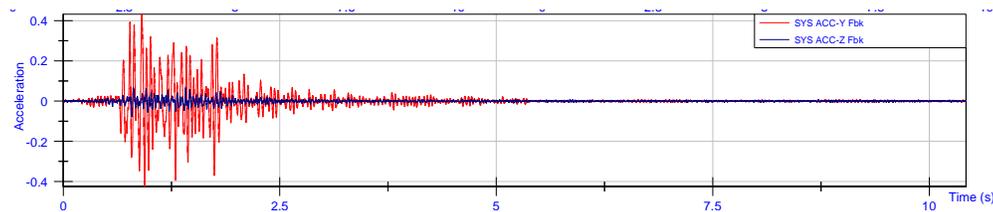


Figure 15. TH for Petrovac, SF 1:9

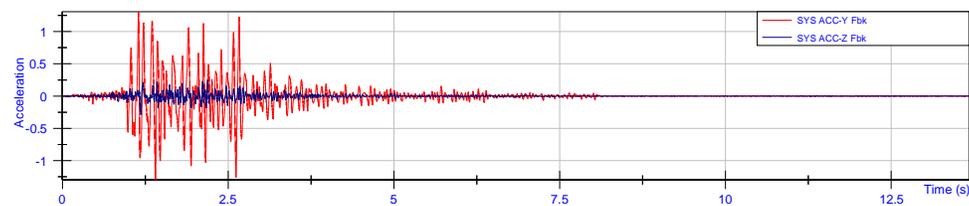


Figure 16. TH for Petrovac, SF 1:6

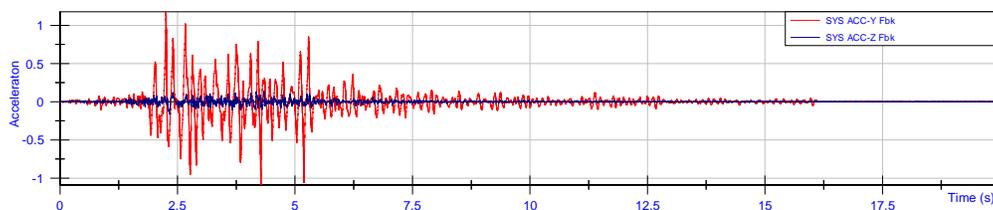


Figure 17. TH for Petrovac, SF 1:3



The shaking table located in the Dynamic Testing Laboratory at IZIS enables programmed generating of translational vibrations in the horizontal and vertical directions. A total of 39 tests were carried out, of which 14 were conducted for the purpose of periodically determining dynamic characteristics and checking model stiffness degradation (Random and Sweep), while the other 25 tests were seismic tests (Petrovac) that made it possible to monitor model response and to monitor the development of the failure mechanism. An overview of the conducted tests is shown in Table 2.

Mark	Type of excitation/input intensity/SF	Mark	Type of excitation/input intensity/SF
Test_01	Random / 3-55Hz / a=0.01g / X	Test_21	Random / 3-55Hz / a=0.01g / V
Test_02	Random / 3-55Hz / a=0.01g / Z	Test_22	Petrovac / Y=1.49g / Z=0.75g / SF 1:9
Test_03	Sweep / 3-55Hz / a=0.01g / X	Test_23	Petrovac / Y=1.79g / Z=0.85g / SF 1:9
Test_04	Sweep / 3-55Hz / a=0.02g / X	Test_24	Petrovac / Y=1.90g / Z=0.90g / SF 1:9
Test_05	Sweep / 3-55Hz / a=0.02g / X	Test_25	Petrovac / Y=2.1g / Z=1.6g / SF 1:9
Test_06	Sweep / 3-55Hz / a=0.02g / X	Test_26	Random / 3-55Hz / a=0.01g / H
Test_07	Petrovac / Y=0.04g / Z=0	Test_27	Random / 3-55Hz / a=0.01g / V
Test_08	Petrovac / Y=0.02g / Z=0	Test_28	Petrovac / Y=2.10g / Z=1.25g / SF 1:9
Test_09	Petrovac / Y=0.07g / Z=0.05g	Test_29	Petrovac / Y=2.30 g / Z=1.50g / SF 1:9
Test_10	Petrovac / Y=0.14g / Z=0.12g	Test_30	Petrovac / Y=2.38g / Z=1.8g / SF 1:9
Test_11	Petrovac / Y=0.27g / Z=0.20g	Test_31	Petrovac / Y=0.38g / Z=0.15g / SF 1:6
Test_12	Random / 3-55Hz / a=0.01g / H	Test_32	Petrovac / Y=0.74g / Z=0.30g / SF 1:6
Test_13	Random / 3-55Hz / a=0.01g / V	Test_33	Petrovac / Y=1.35g / Z=0.60g / SF 1:6
Test_14	Petrovac / Y=0.24g / Z=0.16g / SF 1:9	Test_34	Petrovac / Y=2.40g / Z=0.90g / SF 1:6
Test_15	Petrovac / Y=0.44g / Z=0.38g / SF 1:9	Test_35	Random / 3-55Hz / a=0.01g / H
Test_16	Petrovac / Y=0.51g / Z=0.40g / SF 1:9	Test_36	Random / 3-55Hz / a=0.01g / V
Test_17	Petrovac / Y=0.69g / Z=0.45g / SF 1:9	Test_37	Petrovac / Y=0.40g / Z=0.20g / SF 1:3
Test_18	Petrovac / Y=1.01g / Z=0.50g / SF 1:9	Test_38	Petrovac / Y=1.24g / Z=0.46g / SF 1:3
Test_19	Petrovac / Y=1.25g / Z=0.65g / SF 1:9	Test_39	Petrovac / Y=2.30g / Z=1.15g / SF 1:3
Test_20	Random / 3-55Hz / a=0.01g / H		

Table 2. Specification of the conducted tests



Due to the comprehensiveness of the conducted research, this paper will present and analyze the displacements of characteristic points of the bridge model for the test marked Test_38 and the model failure mechanism that followed in the final test marked Test_39.

The measured displacements of the bridge model for input acceleration for Test_38, for which the scaling factor is 1:3, are shown in Table 8. For the measurement point of displacement transducer LVDT1 placed at the top of the model arch, which measured vertical displacements, a displacement of 17.24 mm was measured. The displacement transducer LP3, also installed at the top of the bridge arch, measured the horizontal displacement value of 31.65 mm. For the displacement transducer LVDT8, placed on the rows 46 and 48, where it measured relative horizontal displacements, we the value of 0.01mm was read. For the measurement point of displacement transducer LVDT2, which was placed on the arch row number 69, a displacement of 18.89mm was measured.

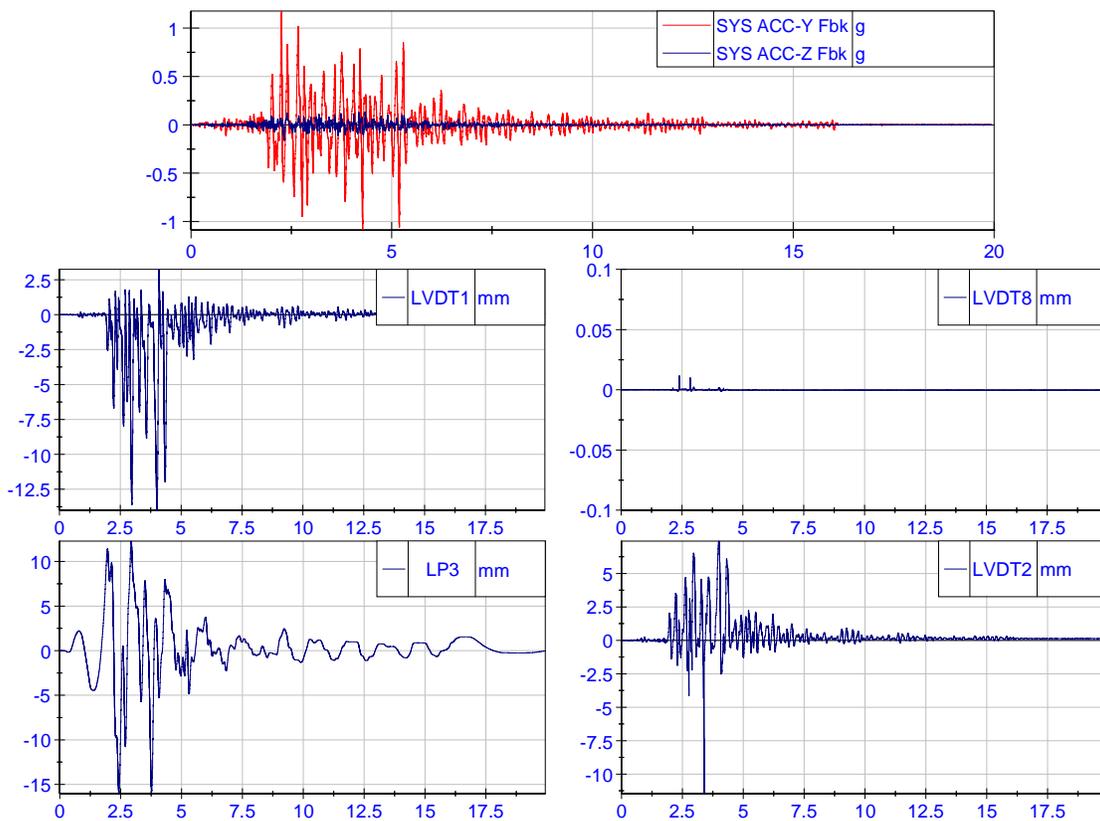


Figure 18. Input acceleration and model response at characteristic points for Test_38

Mark	LVDT1	LP3	LVDT8	LVDT2
Displacement (mm)	17.24	28.09	0.01	18.89

Table 3. Arch top displacement values



For the last test, marked Test_39, with input acceleration of 2.27g, scaled by the scaling factor 1:3 in the time domain, in which the model failure occurred, we can state that it is not realistic to happen for the prototype location, and it was carried out for the purpose of analyzing the behavior type and determine the model failure mechanism. The model failure mechanism shown in Figure 19 is the result of irreversible model deformations, large displacements, stiffness degradation, failure of implemented connection elements, which led to the stability loss manifested by the characteristic mode of structural failure.

Development of cracks on the bridge model confirmed that the top zone of the bridge arch and the zone of third points are the key damage points for these types of structures. The latter was confirmed by the maximum vertical and horizontal displacements measured at these places.

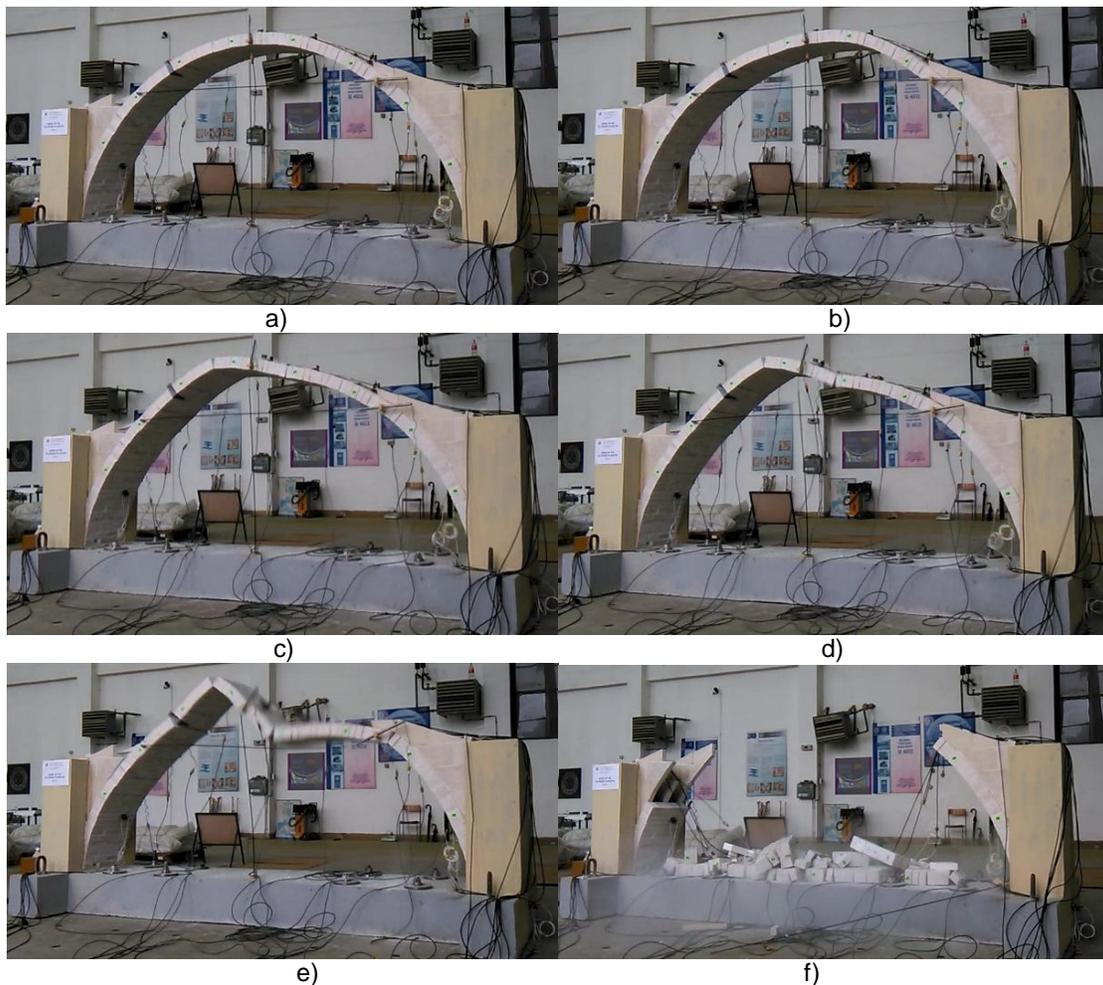


Figure 19. Bridge model failure mechanism

5. CONCLUSION

Experimental tests on arch segments of the Old Bridge in Mostar are presented in the paper at scale 1:3 for actions of different types of quasi-static loads for the purpose of determining the bearing capacity of connection elements. The paper also presents testing of the model of the Old Bridge in Mostar at scale 1:9 on the shaking table for the purpose of determining the bearing capacity and model failure mechanism. Both conducted investigations provided us



with useful information on the type of behavior of both connection elements and the structure as a whole. The results of the conducted tests will be used to develop and verify numerical models, which will complete the conducted activities and give a high-quality contribution to the protection of this type of structures, which are also cultural monuments in a large part.

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REFERENCES

1. ČelićDž.; M. Mujezinović: Stari mostovi u Bosni i Hercegovini, Sarajevo, 1998.
2. Čolak, I.: Kratki prikaz revitalizacije lokaliteta Starog mosta, E-zbornik, Faculty of Civil Engineering University of Mostar, Mostar, 2013.
3. Gojković M.: Stari kameni mostovi, Naučna knjiga Beograd, 1982.
4. Gotovac, B.: Numerički modeli luka Starog mosta, Draft varijanta revizije projekta rekonstrukcije Starog mosta u Mostaru, Omega engineering, Mostar, 2003.
5. Gotovac, B.: Ponovna izgradnja Starog mosta, Ceste i mostovi, glasilo Hrvatskog društva za ceste, br. 7-9, str. 23-33, Zagreb, 2004.
6. Kustura M.: Investigation of Seismic Stability of the Old Bridge in Mostar, Master's Thesis, Skopje 2009.
7. Kustura M.: Investigation of Seismic Behavior of Stone Arch Bridges Including the Effect of Connection Elements, Dissertation, Skopje 2018.