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SEISMIC PERFORMANCE AND RETROFIT OF A HISTORIC MONUMENT ARCH BRIDGE

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ABSTRACT

Seismic performance of the oldest reinforced concrete arch bridge in Bosnia and Herzegovina is presented in this paper. The bridge was constructed in the late 1897 as the first reinforced concrete arch bridge during the Austro-Hungarian monarchy in Bosnia and Herzegovina. Several rehabilitation works were done however, no mayor interventions were ever done on this structure. Inadequate maintenance of the structure as well its inappropriate usage, passing of heavy vehicles (for which the bridge was not designed) and their long retaining on the bridge, as well as atmospheric influences have led to it degradation. The bridge was declared a national monument in 2009. In order to get as much as possible information about the bridge structure nondestructive and minor destructive tests were conducted in order to make an adequate numerical model. A rehabilitation of the structure was proposed following the ICOMOS guidelines and Venice Charter.

As dynamic characteristics of bridge structures are the basis of structural dynamic response and seismic analysis, and are as well an important target of health condition monitoring, they were measured and calculated for the original structure and only calculated for the rehabilitated structure. Comparison of the results was done.

Keywords: Rehabilitation; Seismic effects; Cultural Heritage; Venice Charter; Reinforced arch bridge

1. INTRODUCTION

Importance of historic structures' preservation as representatives of a certain period and their historic significance to the culture heritage has to be emphasized and cherished. This is something that for many centuries has been neglected in Bosnia and Herzegovina. The public awareness of the value and importance of historic structures is not so high. The aim of this paper is to present the work done on a historic structure, a reinforced concrete arch bridge, which was the first attempt of a Check Engineer J. Pelikan/Šustera in the late 1897 to make such a structure. The bridge is located in the heart of Sarajevo Old Town. It is called *Careva ćuprija*, which means the Emperor's Bridge as it is located next to the Emperor's Mosque. The unawareness of the importance of this structure lies in the fact only in 2009 it was declared a national historic monument of Bosnia and Herzegovina.

It is believed that this is the oldest bridge of this type and the only arch bridge with L-type reinforcement. The bridge was several times rehabilitated unfortunately its original appearance has been jeopardized and to a certain extend destroyed as its rehabilitation was done by engineers which did not take into account the ICOMOS recommendations and did not follow the Venice Charter. Lack of knowledge, ignorance and inadequate engineering measures can lead to losing the cultural value of structures.

2. SEISMIC ACTIVITY IN BOSNIA AND HERZEGOVINA

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It is well known that Bosnia and Herzegovina is one of the active seismic zones in the Balkans, which makes a part of the Trans-Mediterranean-Asian Seismic belt. According to the Euro Mediterranean Seismic Hazard Map developed in 2005, Bosnia and Herzegovina falls in the Moderate Seismic Hazard having the PGA in the range of 0.08–0.24 g. A High Hazard (PGA > 0.24 g) is evident in the south-west part of the country (Figure 1) (European-Mediterranean-Seismic-Hazard-Map 2005).

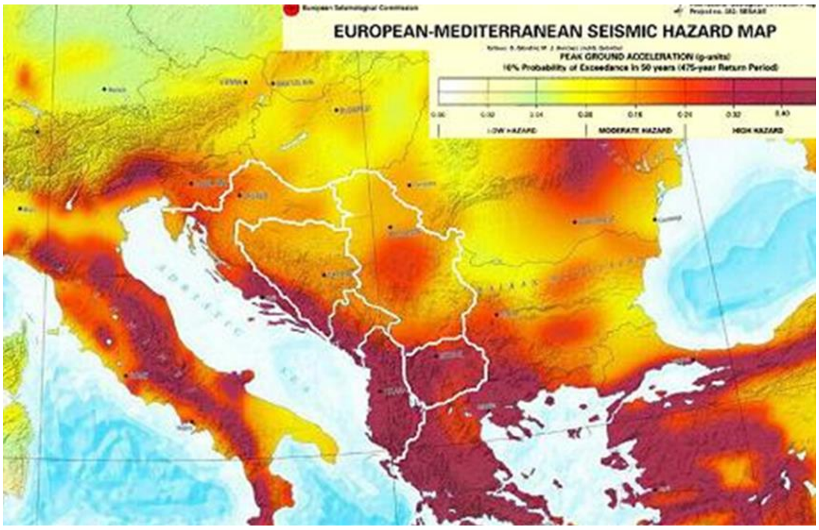


Figure 1. European-Mediterranean-Seismic-Hazard-Map
(http://www.preventionweb.net/english/professional/maps/v.php?id=10049)

The strongest, but seldom earthquakes are manifested within the Sarajevo Thrust (Figure 2) (Ademović 2011, 2012, Ademović and Oliveira 2012). B&H was hit by several devastating earthquakes with the highest intensity and magnitude located in Ljubinje, Treskavica (mountain near Sarajevo) and Banja Luka. According to the seismological data, annually 1100 earthquakes of intensity lower than III by Mercalli-Cancani-Sieberg (here in after MCS) were registered in B&H, while in the last 104 years 1084 earthquakes of the Richter's magnitude greater than 3 were registered as well (Ademović 2011, 2012). The strongest earthquake that struck Sarajevo region (30km to the south) was in 1962 at the location of the biggest fault line near the city of Sarajevo. The magnitude by Richter scale was six (6). In this respect, possible seismic effects on the bridge had to be checked as well.

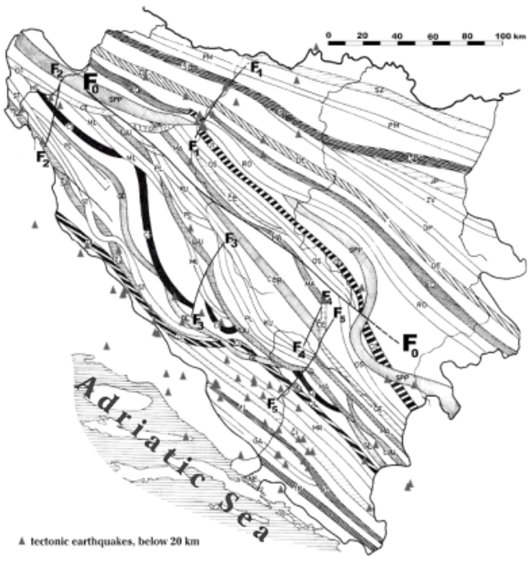


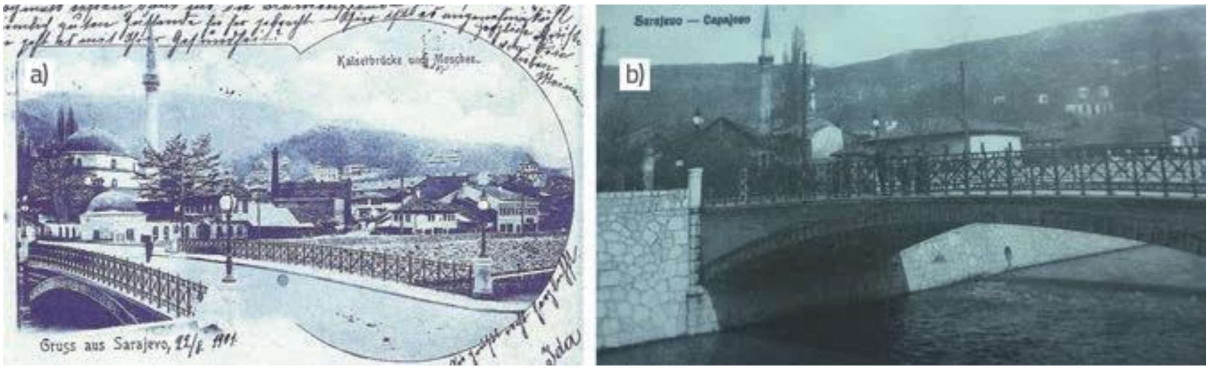
Figure 2. Main deep thrusts (to 25 km): Sarajevo fault (FoFo), Gradiška fault (F1F1), Bihać fault (F2F2), Livno fault (F3F3), Jablanica fault (F4F4) and Mostar fault (F5F5) (Papeš 1988)

3. ASSESSMENT OF EXISTING BUILDINGS

Characterization of an existing structure is a very complex task, which requires a specific multidisciplinary evaluation methodology for its assessment, as stated in the ICOMOS-Recommendations for the Analysis, Conservation and Structural Restoration of Architectural Heritage in 2003. With adherence to this methodology, a clear assessment of the current physical state of the structure can be obtained. With this knowledge, numerical models can be developed and calibrated to define accurately the structural form and mechanisms. The methodology's two phases were followed; Knowledge phase (historical research; description of the structure - geometry and materials; damage survey; in-situ and laboratory tests); and, Numerical Analysis phase (definition of the type of analysis, models and tools) (Ademović 2012).

3.1 Careva Ćuprija-Emperor's Bridge

Careva ćuprija, which means the Emperor's Bridge, was built in 1897. It was built as the first single-arch reinforced concrete bridge in Sarajevo and, with the span of 25.36 meters; it was the largest structure of this type in the Austro-Hungarian monarchy (Figure 3). According to some data, the bridge was built based on the design made by the Czech engineer J. Pelikan / Schuster (Ademović et al. 2017).



a) b)

Figure 3. a) The Careva Ćuprija Bridge in 1901; b) Photograph of the Careva Ćuprija Bridge 1900.-1910 (http://radiosarajevo.ba/photo/galerija/12787)

Due to the impossibility to obtain the original design, in order to obtain as much as possible data about the bridge and to make the diagnostics of the current state of the bridge, a very detailed visual inspection, nondestructive and minor destructive tests had to be conducted.

Very detailed optical survey of the bridge was conducted; all elements of the bridge were measured in detail; visual inspection was done and very detailed crack patterns were drawn which was essential for the diagnosis. Visual inspection revealed that the bridge consists of one reinforced concrete arch with a rather flat, almost radial alignment, with the height of about 5 m at the center of the bridge. The arch structure is defined by the opening of about 25.15 meters in length. The rise of the bridge arch is about 2.60 m.

A traditional way of foundation has been reviled once the stone blocks were removed from the bank abutment walls (Figure 4).

Figure 4. Abutment stone blocks at the left bank of the river and situation after their removal (author's photo)

The bridge is founded in a traditional way on a structure composed of stone slabs on which the bank abutments of limestone were constructed (local white Hreša stone) as supports for the arch structure. Complementary diagnostic methods were done, based on non-destructive and minor destructive tests methods to allow a wide view of the problem. In this respect, cores were taken out of the structure in ordered to determine the compressive strength of concrete, determine the presence of deleterious matters in concrete, determine the mix composition of concrete, etc. In order to determine the location and the type of the steel reinforcement minor removal of the concrete cover was done and type of steel was determined, as well as, the degree of corrosion (Ademović et al. 2017).

On site tests and laboratory investigations revealed that the arch concrete was of a concrete class MB 20 (equivalent to C15/20 according to Eurocode 2). The structure was reinforced by rigid set of 20 2L 60 x 60 x 4mm at a distance of approximately 45 cm (Figure 5). The steel was classified as steel class Č 0545 according to JUS standards (according to EN 10027-1 E295, and DIN St 50- 2), with the tensile strength of 470 N/mm^2, and the yielding strength of 285 N/mm^2 (Ademović and Kurtović 2015, Ademović et al. 2017).

Figure 5. Distance between rigid reinforcement sets (author's photo)

The connection of the rigid reinforcement was performed by a steel plate (46 x 13 cm) about 6 mm thick and a set of six rivets on each side. Placement of the rivets is at an interval of 6 cm. Inner spacing between the rivet sets is 13.5 cm, while the distance from the edge of the steel plate to the first (last) rivet is 4.5 cm. The steel corrosion and scaling were registered on the steel plates used as connections for rigid reinforcement (Figure 6). Further details regarding the visual inspection can be found in (Ademović and Kurtović 2015, Ademović et al. 2017).

Figure 6. Connection of the rigid reinforcement (author's photo)

3.2 Numerical model of the existing structure

Geometric characterization of the bridge was done by detailed topographic survey and this was used as an input in the geometrical modeling of the bridge. Material characteristics were estimated based on the results of in situ and laboratory tests conducted within an experimental campaign. On the basis of experimental investigations it was determined that the thickness of the arch varies a bit so an average value of 45 cm was taken in the calculations and concrete C15/20 was adopted. The unit weight of the backfill was taken to be equal to 18.0 kN/m^3. As per on site tests it was determined that the pedestrian carriage way was done by factory-mixed concrete with dolomite aggregate, most probably originating from the post-war decades of the past century, or from this century (Ademović et al. 2017). In that respect, the unit weight of this concrete is 25 kN/m^3. The carriageway is made of gabbro cubes having a unit weight of 29 kN/m^3.

The finite element method and specifically the Tower software was used for the analysis of this structure (Tower 7 2015). Shell elements with six degrees of freedom were used in modelling adopting the assumption that the effects from the walls are not transferred to the arch structure and that the connection of the arch and the abutments does not involve transfer of bending moments, which is quite understandable due to detail of the arch support on the abutment.

Modal analysis is a rapidly growing field in vibration research. Modal analysis is a process of describing a structure in terms of its natural characteristics, which are the frequency, damping and mode shapes - its dynamic properties (Avitabile 2001). It is used effectively in the identification of structural dynamic characteristics, and it has become a flourishing area of vibration research. Finite Element (FE) method as an analytical technique was used to determine the dynamic characteristics of the bridge structure. If there is to be a change in the mode shapes of vibrations or frequencies this would clearly indicate a change in the structural conditions.

The fundamental modes and frequencies of the existing bridge (Figure 7) indicated that it is a rather rigid structure. The values of frequencies are given in Table 1.

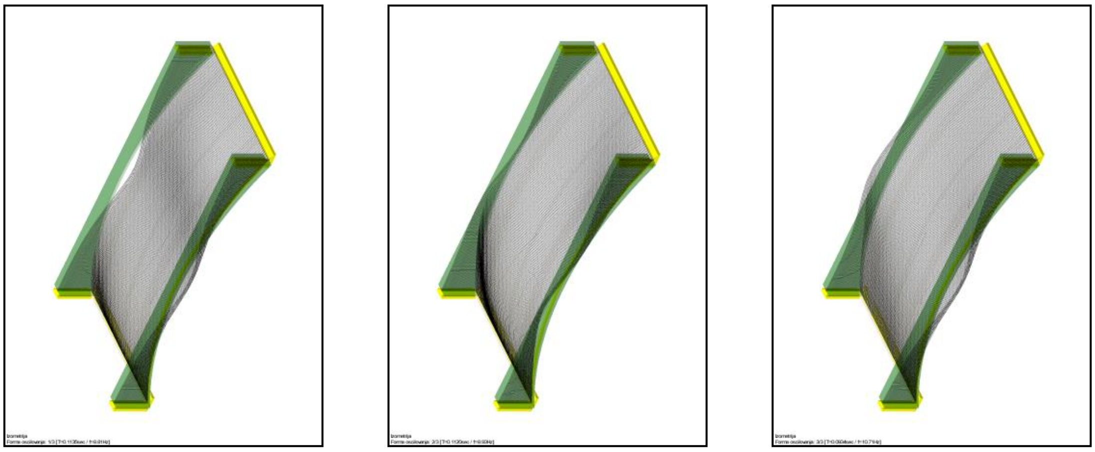


Figure 7. Fundamental modes and frequencies

Table 1. Fundamental periods and frequencies of the existing structure

Mode	Period [s]	Frequency[Hz]
1	0.1135	8.81
2	0.1120	8.93
3	0.0934	10.71

3.3 Experimental identification of the modal parameters

The numerical bridge model and the theoretical dynamic parameters (here only frequency will be presented) were compared with the measured values on the site. This is a key step for calibration and validation of the numerical model. In order to obtain the dynamic characteristics experiment was done in the sense that a truck passed over a 5 cm plank. As the bridge is a national monument, special care was taken during this procedure and the truck was passing at a speed of 15 km/h. This caused vertical excitation of the bridge, and provided information about the global characteristics of its deformability. Estimation of natural frequencies was conducted by utilizing the commercial computer software (here Catman 5.0) directed to signal processing and modal analysis. The response measurement involved four accelerometers, type HBM B12/200 located at the carriageway of the structure. Figure 8 shows the calculated power spectra using the Fast Fourier Transform (FFT).

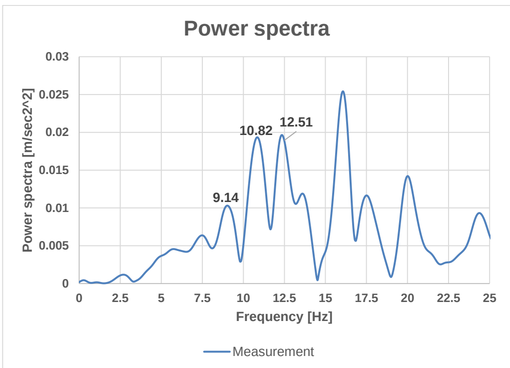


Figure 8. Measured frequencies

Good consistency is seen between the numerical model and experimental investigations.

3.4 Numerical model of the rehabilitated structure

Based on the static calculations (Ademović et al 2017) it was concluded that it was necessary to strengthen the structure. As it is a national monument following the regulation provided by the Venice-Charter ICOMOS (1964) were respected. In that sense, it was proposed to strengthen the structure with steel meshes (MA 500/560) Q524 on the intrados and extrados and with sprayed concrete MB 20 (C15/20). The thickness of concrete in the extrados is planned to be 5 cm while on the intrados it would be 10 cm. Shotcrete is traditionally used to increase the arch thickness in order to increase the carrying capacity, and to stabilize and protect structures exposed to atmospheric conditions. A large number of Victorian masonry bridges and arch structures in England were strengthened in this way (Page 1993). Of course, the infill material would be changed, new railing would be installed (as the original one-see Figure 2), as well as new granite stone pavement. This all was taken into account in the calculation of the fundamental periods and frequencies of the rehabilitated structure (Figure 9 and Table 2).

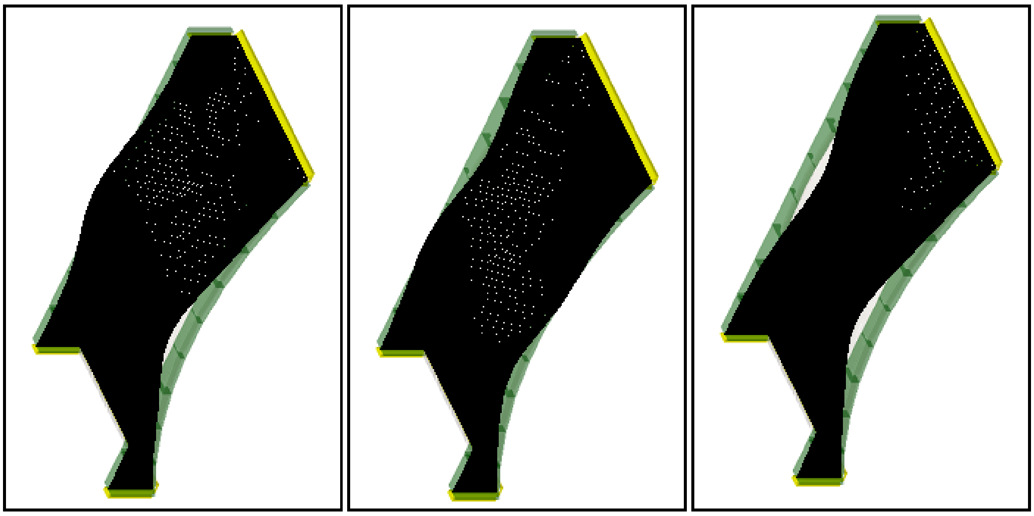


Figure 9. Fundamental modes and frequencies of rehabilitated structure

Table 2 Fundamental periods and frequencies of the rehabilitated structure

Mode	Period [s]	Frequency[Hz]
1	0.10	9.91
2	0.099	10.08
3	0.086	10.57

As it can be seen, the difference for the first two modes is from 1.10 to 1.15 Hz. The structure is a bit more flexible; however, its dynamic characteristics did not change much, which is more than acceptable. The type of modes stayed the same as in the existing structure.

3.4 Dynamic testing of the bridge

As the structure is a national monument, it is of the utmost importance to use non-destructive testing techniques to determine the natural frequencies and natural modes. The frequencies, damping ratio and mode shapes can be acquired through ambient vibration test and modal analysis (Chang et. al 2001). This is of the supreme importance, as this will indicate are there any additional damages on the structure, which might have affected its stiffness or even mass and in such a way affected the dynamic characteristics of the bridge. It is foreseen to apply the methodology for the dynamic-based assessment of a reinforced concrete arch bridge as presented by Gentile (Gentile 2006). This approach was based on ambient vibration testing, output-only modal identification and updating of the uncertain structural parameters of a finite element model of the bridge. Once this data is, obtained new model calibration will be done. The element that can have effect on the modal response of the structure, would be the support conditions as the material characteristics have already been implemented in the finite element method.

As mentioned above, standard dynamic testing of the bridge with a track passing over the bridge at a speed of approximately 15 km/h was done. Taking into account the position of the bridge, with careful driver of the truck, fortunately it was possible to undertake such actions (Figure 10). The dynamic testing of the bridge started and as presented in the previous paragraphs some data have been recorded and analyzed.

Figure 10. Bridge location

Additionally, in the spring of 2018 an acquisition campaign is planned where the traffic would not be interrupted, but on the contrary, it will be used to excite the structure, all with the goal to capture the modal frequencies and modal shapes. Based on the numerical model it is foreseen that the first mode would be dominant. It is planned to measure the vibrations with high sensitive piezoelectric accelerometers that are able to register in the range of 0-100 Hz. The measurement is planned to be conducted with Spider 8 and the data acquisition and storage of dynamic data use of an analog-to-digital (A/D) converter in the measurement chain (again Catman 5 will be used). The Frequency Domain Decomposition (Brincker et al. 2001) will be used to process the data that would then be used for updating of the current FE model. The reasoning behind this is, that based on the numerical models, it was seen that the natural frequencies and mode shapes are not well separated. If they had been than the classical technique could be applied. In the case of close modes quite often it is rather difficult to detect these modes, and even if detected, this data is very biased. In this case, the frequency estimates are limited by the frequency resolution of the spectral density estimate. Finally, correct estimation of damping is not possible and rather uncertain. Even though it has all of these disadvantages, it is frequently used do to its simplicity. The FDD eliminates all the drawbacks of the classical technique on one hand and on the other, it is still user friendly, but additionally as one is dealing with the spectral density function the physical meaning is straight forward. Once the rehabilitation of the bridge is done, it is planned to conduct a new acquisition campaign with the goal of validation and calibration of the model of the rehabilitated bridge.

5. CONCLUSION

In order to preserve the cultural integrity and to pass its values on to the next generations it is of the utmost importance to protect the cultural and historical heritage. As these structures, represent a landmark of a certain period it is important to preserve them and try to extend their life as much as possible respecting the Venice Charter. The rehabilitation works should be ones of minimum invasion.

In this way, the history of a certain period will continue to live. Two numerical models were done. One of the existing structure and the other of the rehabilitated one. Dynamic characteristics (eigen frequencies and eigen modes) were compared and it was seen that the difference is very small. The rehabilitated structure is a bit more flexible; however, its dynamic characteristics did not change much, which is more than acceptable. The type of modes stayed the same as in the existing structure. Numerical calibration and validation of the model representing the existing structure was done by means of frequency identification through dynamic bridge testing. In order further to validate the numerical model of the existing as well of the new rehabilitated structure, it is planned to conduct ambient vibration tests in the spring of 2018 of the current structure as well as after the rehabilitation of the structure. In that respect, it is planned that during the acquisition campaign the traffic would not be interrupted, but on the contrary it will be used to excite the structure, all with the goal to capture the modal frequencies and modal shapes.

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