STRUCTURAL ASSESSMENT OF STONE-ARCH BRIDGES THROUGH PHOTOGRAMMETRY

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ABSTRACT:

The present study examines the structural assessment of Pashas bridge, located at the Western Makedonia, in Greece. This stone arched bridge, which is declared cultural heritage monument, was built during the end of 17th century and it was destructed during the 2nd civil war, in 1941 by British and New Zealander soldiers aiming to end the German invasion to the South of Greece. It was considered the largest bridge in Macedonia, with a length of more than 100 meters, 6 arches, the biggest one of which was almost 15 meters high. In its current form it is partially collapsed.

1. INTRODUCTION

The structural assessment of stone-arch bridges is a very interesting scientific field for which very important scientists have argued, since 17th century. Initially Galileo argued against the geometrical and structural similarities. Leon Batista Alberti declares the absolute safety of the semi-circular geometry. Leonardo Da Vinci with experimental arguments connected the importance of geometry with the safety of the structure. The following centuries Couplet, Philippe De la Hire, Fierté Bouguer, Giacomo Bernoulli, Bossut, Mascheroni, Salimbeni investigated the structural problem of stone bridges proposing mathematical equations. In addition, Charles Coulomb developed important theories adopted by Gauthey and Jean Rodolphe Perrone. Army engineer Audoy continues Coulomb’s theories defining the fracture geometric position of a stone bridge. Lame and Clapeyron, Cauthey and Navier also investigated the structural problem of stone bridges. Finally during the mid 19th century F.J.Gerstner and Mery also studied the strength of these important structures. All previous scientists proved that the geometry of stone arch bridges plays the most important role for their structural integrity.

The present study examines the structural assessment of Pashas bridge, located at the Western Makedonia, in Greece. Pasha stone arch bridge was declared cultural heritage structure. It was built during the end of 17th century and it was destructed during the 2nd civil war, in 1941 by British and New Zealander soldiers aiming to end the German invasion to the South of Greece. It was considered the largest bridge in Macedonia, with a length of more than 100 meters, 6 arches, the biggest one of which was almost 15 meters high. During Kozani’s earthquake, in 1995, Pashas bridge was further damaged. Figure 1 depicts Pasha’s bridge before its collapse.

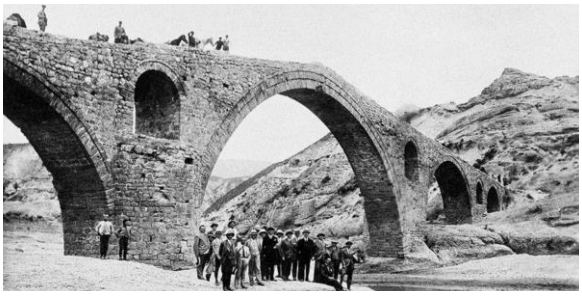

Figure 1. Depiction of Pasha’s bridge before its collapse

Pashas structural system is discussed, together with specific construction details. The structural finite element model is designed and meshed using photogrammetric data given by a variety of tools and techniques, including photogrammetry, UAVs, laser scanning. The use of these modern techniques allows the development of very realistic structural geometries leading to very accurate numerical 3D models.

Furthermore, the basic assumptions of three-dimensional (3-D) numerical simulations of the dynamic response of Pasha bridge, before its destruction is discussed based on all selected information. The results of these numerical simulations are presented and discussed. Its seismic response is studied subsequently in some detail as predicted from the linear numerical simulations under combined dead load and seismic action.

Issues that influence the structural integrity of such bridges, focusing on geometric details, are discussed combined with the results of the numerical investigation. Finally, a brief discussion of maintenance issues is also presented.

The presented study is part of the effort fulfilled by multiple research groups from the Aristotle University of

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Thessaloniki (AUTh) towards to its restoration. The restoration of an old bridge is a complicated and multi-faceted process, particularly when the structure holds significant cultural heritage value.

Summarizing, the present work is focusing on the first stages of the restoration study of this important monument, where photogrammetric techniques and structural assessment are combined towards this goal. The entire restoration study was assigned to AUTh by the Ministry of Culture and Sports and the Region of Western Macedonia for a period of 18 months. In particular, this study includes:

1. Collection of historical data and historical documentation of construction [1-4],
2. Geometrical, Structural and Architectural description of the existing situation.
3. Description and recording of the construction phases.
4. Collection of samples of building materials and documentation of bearing organism and materials.
5. Collection of geological, geotechnical and foundation data
6. Collection of hydrological data
7. Seismological data collection
8. Recording of damages and collapses of the bridge
9. Assessment of the remaining bearing capacity of the existing bridge sections
10. Preliminary investigation for inclusion in the overall environment.
11. Preliminary architectural-morphological design and formulation of appropriate and documented proposals, which are required for the purpose of restoring the bridge
12. Preliminary selection of materials and structural elements
13. Preliminary structural design based on the existing parts that need restoration and maintenance and the extensive parts that have been damaged.

This manuscript discusses the methodology used for the topographical measurement of the existing parts, the development of a 3D model and the determination of the full geometry of the stone bridge. Following, the structural assessment of the structures is examined.

2. TYPOLOGY AND GEOMETRY

The determination of the typology and the geometry of the bearing system of Pasha stone bridge presents a significant difficulty. There are some existing parts of this structure, while several important parts are non-existent due to its collapse 80 years ago. These large sections that collapsed, including the very important central arch, do not exist today since all their components have been removed by the locals and it is not possible to identify them. Therefore, the following methodological approach will be followed to determine the geometry of the Pasha’s bridge bearing system:

- Collection and study of historical data and photographs [1-4].
- On-site measurements of the existing situation with high precision surveying methods.
- Combining the on-site measurements with historical photographic material to approximate the geometry of the collapsed shape to derive the overall geometry of the bridge's load-bearing system.
- Topographic placement of the bearing system of the bridge in the existing terrain.

Figure 2 and 3 depicts some of the found photographic material that was utilized in order to approach the actual geometry. A key aspect of the restoration process is the need to properly record, document and assess the current state of the stone bridge. Photogrammetry, using images to create accurate 3D models of objects or structures, can be a particularly useful tool. By combining the use of unmanned aerial vehicles (UAVs) that support the acquisition of a huge number of images from many angles, and specialized software, a detailed 3D model of the stone bridge in its existing state can be created. Thus, the 3-D model of the bridge was measured and created, on which the study of its repair-restoration and reconstruction will be based.

The first step was the creation and measurement of photostable points in the surrounding area of the bridge and on its surface. The creation and marking of the photostable points in the surrounding area was done using nails and marking spray so that they are visible in the images. They were measured using geodetic GPS and with an accuracy of 10mm. The measurement of the photostable points on the surface of the bridge was done using a geodetic station (total station) with selected characteristic points on the bridge.
Two models of unmanned aerial vehicles were used, specifically two quadcopters from the company DJI to capture the images (DJI Phantom 4 and DJI Phantom 3 Pro) and a total number of 1350 photographs were captured, through 15 flights with 20 minutes duration each and overlap percentage of pictures 80%. The flight height for these shots was 30 meters. High overlap was chosen so that there is no problem connecting overlapping images during processing. Images were processed using Photoscan Agisoft Metashape software. Finally, the 3D model of the existing parts of the bridge were developed, as depicted in figure 6.

Figure 2. North view of the bridge before its collapse

Figure 3. South view of the bridge before its collapse

Figure 4. Top view of existing parts of the piers

Figure 5. Side view of existing parts of the piers

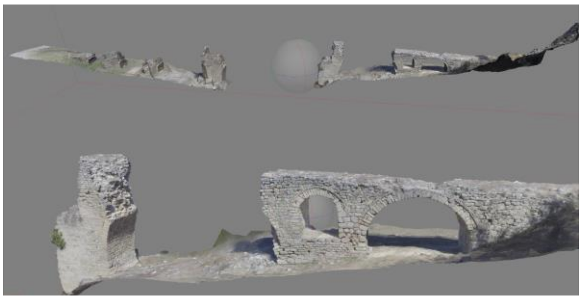


Figure 6. Developed model of the existing parts.

3. STRUCTURAL DETAILS

Figure 7 depicts the North view of the proposed geometry for the reconstruction of the stone bridge, according to the topographical and architectural documentation. As can be seen, the bridge is composed of 6 arches A1-A6, two abutments, Western and Eastern, called AB1 and AB2 and five intermediate piers, P1-P5. The arches of the bridge have the following diameters from west to east: 6.14 m – 8.50 m – 15.52 m – 28.76 m – 14.69 m – 6.20 m The 4rh arch, A4, is the middle arch with height 15m, which bridges the Aliakmonas river, and it is supported by piers P3 and P4. The central middle arch is made of a primary and a secondary arch. On the two main piers, P3 and P4, there are large relief openings (figure 8). Relief openings of smaller dimensions are also presented on piers P2 and P5. The relief openings are well constructed and help to reduce weight and hydrodynamic pressures in an extreme flood situation. It is a construction technique found in many arches with relatively large dimensions (figure 1). P3 and P4 are strengthened by widened piers with pyramidal cross section. The shape of the piers leads to lower resistance to the river flow and lower hydrodynamic pressures in flood conditions. The dimensions of the cross sections of the piers range from: 4.80m to 5.83m wide and 3.30m to 8.45m length. The average width of the deck is about 3.30m with the side parapets and 2.60m without them.

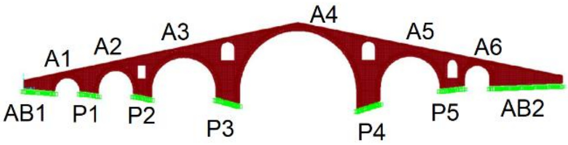


Figure 7. Sketch of the full geometry of the bridge and its structural members

Figure 8. Photograph of the existing pier P4 with the relief opening above it, and the developed architectural view

4. MATERIALS

Pasha's bridge structural system is constructed with stone masonry parts. In order to identify the mechanical and physico-chemical properties of the used materials, a number of samples were taken from the existing parts, figure 9.

These samples of mortar were subjected to the listed above tests:

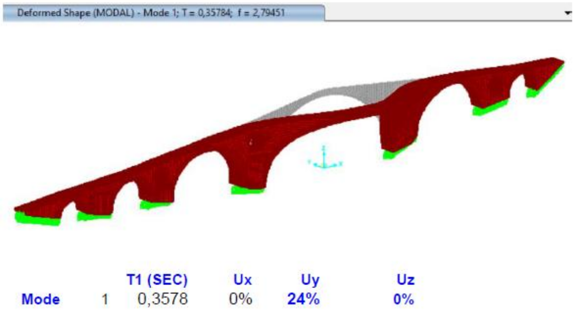
1. color determination
2. stereoscopic control
3. granulometric analysis
4. chemical analysis
5. determination of water-soluble salts
6. determination of porosity
7. determination of specific gravity
8. determination of compressive strength

The obtained results were used to understand the existing material and suggest compatible restoration materials. The composition of the mortars is calcite with the use of soil material with pozzolanic action. The aggregates used are natural and predominately fine-grained in an even distribution and in a powder/aggregate ratio of the order of 1/2.5. The maximum grain size of the aggregates is 8mm. The compressive strength is 4.0-4.9MPa while the porosity ranges from 18-20%. From the evaluation of the analysis results of the mortars, based on its composition and structure, compositions for the reconstruction of the collapsed parts will be defined, compatible with the old materials, which preserve the physico-chemical characteristics of the original mortar with the necessary adjustments to make it workable and obtain strength compatible with the existing ones. The high presence of salts in the materials indicates the requirement of high porosity for the structure to "breathe".

Figure 9. Sample of mortar taken from existing pier

5. STRUCTURAL ASSESSMENT

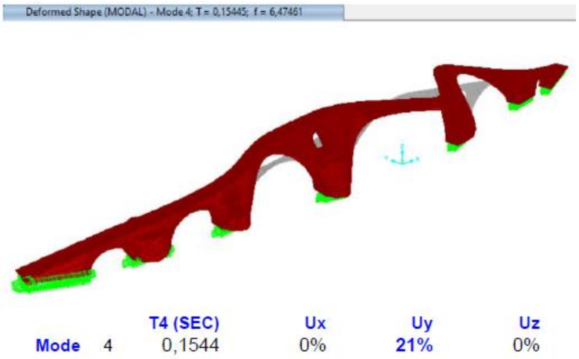
In this section the structrural performance of the studied bridge is discussed. The methodology of the structural assessment is divided into different categories, the structural assessment of the existing parts and the design of the new parts. To do this, a 3D elastic model was developed using shell finite elements [5-7]. A Young’s modulus equal to 3000 MPa was adopted for the arches, while the Young’s modulus of the rest of the parts was given 2000MPa. The density of the stone masonry was assumed 2.2tn/m3. The structure is fixed support at the bottom end of the piers. The geometry of model is based on the in situ topographical measurements and the architectural documentation as it is described in section 2. Following, the appropriate thickness was assigned to the shell elements according to the measured and predicted thickness of each structural member as it is described in section 3. A number of load combinations were formed to evaluate the bearing capacity of the structure. These load combinations include gravity loads, live loads, seismic type loads and hydraulic pressure imposed by the flow of the river. The seismic type loads are simulated through response spectrum analysis, which is based on the modal analysis of the structure. The following figures depict the dominant modes derived from the modal analysis. Mode 1 is the dominant mode in the out of plane direction with mass participation factor 24%, while mode 4 has mass participation factor 21%, figures 10-11. Mode 1 is the dominant mode in the in plane direction with mass participation factor 33%, while mode 9 has mass participation factor 21%, figures 12-13.



Deformed Shape (MODAL) - Mode 1; T = 0,35784; f = 2,79451

		T1 (SEC)	Ux	Uy	Uz
Mode	1	0,3578	0%	24%	0%

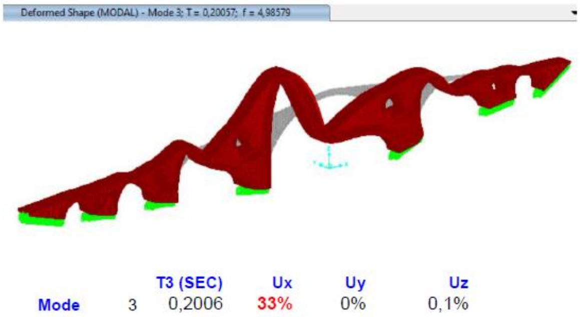
Figure 10. Mode 1 - deformed shape, T=0.358sec



Deformed Shape (MODAL) - Mode 4; T = 0,15445; f = 6,47461

		T4 (SEC)	Ux	Uy	Uz
Mode	4	0,1544	0%	21%	0%

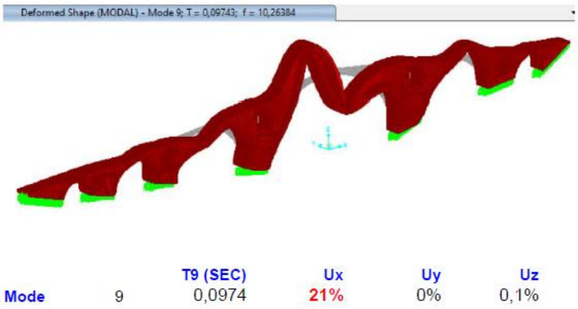
Figure 11. Mode 4 - deformed shape, T=0.154sec



Deformed Shape (MODAL) - Mode 3; T = 0,20057; f = 4,98579

		T3 (SEC)	Ux	Uy	Uz
Mode	3	0,2006	33%	0%	0,1%

Figure 12. Mode 3 - deformed shape, T=0.200sec



Mode		T9 (SEC)	Ux	Uy	Uz
Mode	9	0,0974	21%	0%	0,1%

Figure 13. Mode 9 - deformed shape, T=0.097sec

Based on the modal analysis, response spectrum analysis was carried out using the Spectrum proposed by Eurocode 8. The used spectrum was formed for soil type A, according to the geotechnical study, importance factor 1.0, behavior factor q 1.5 and ground acceleration 0.16g as it is recommended by Eurocode 8 and the Greek national annex. The hydraulic pressure in case of extreme flood was calculated 0.1 MPa applied as a uniform static load up to a level 1m lower than the relief openings of the central piers. Figure 13 depicts the developed maximum principal stresses (MPa) under the seismic load combination with the dominant direction of the seismic loads applied parallel to the out of plane direction of the bridge.

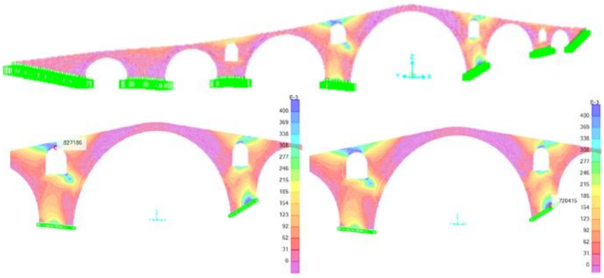


Figure 14. Developed maximum principal stresses under seismic type loads with dominant direction of earthquake loads the out of plane direction.

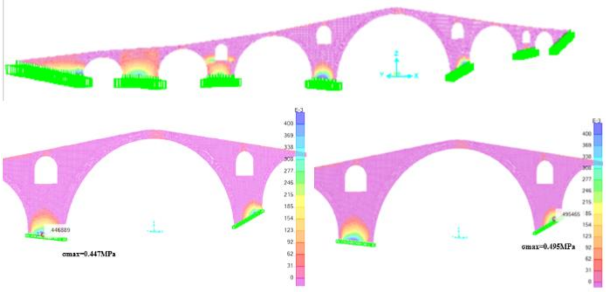


Figure 15. Developed maximum principal stresses under the load combination with dominant action the hydraulic pressure.

The results of all numerical predictions highlighted specific areas as the most critical.

a) Under hydraulic pressure high tensile stresses are developed at the base of the two piers that support the central main arch of the stone bridge. The geotechnical drilling of the bedrock revealed a satisfactory bearing capacity. Therefore, crucial is the quantification of the bearing capacity of the existing piers and the recommendation of repairing – strengthening methodologies required to withstand the developed internal forces.

b) Tensile areas are also created in the relief openings above these middle piers. Therefore, here too the reconstruction of these parts should adopt construction techniques and materials that on the one hand will follow the traditional construction techniques and the corresponding morphological elements on the other hand will be able to safely withstand the predicted demands.

c) In the areas of the main arches, especially the main central arch, the values of the maximum tensile stresses are at lower levels than those of the areas at the base of the piers and in the relief openings above the main piers. Here the reconstruction of these parts should adopt construction techniques and materials that on the one hand will follow the traditional construction techniques and the corresponding morphological elements on the other hand will be able to safely withstand the predicted demands as well.

6. CONCLUSIONS

To sum up, the ongoing investigation of the reconstruction study of the partially collapsed Pasha's stone bridge is discussed here. This investigation is based on historical data, in situ topographical measurements. The combination of the above material led to the topographical and architectural documentation of the bridge's typology and geometry and the production of the 3D model of the full structure. This model was utilized to develop finite element simulations. The numerical predictions indicated that load combination with the hydraulic pressure as dominant action produces the most unfavorable stress distribution at the bottom end of the main piers. Additionally, the load combination with out of plane seismic action as dominant action produces the most unfavorable stress distribution above the relief openings and the main arch. The developed response in terms of maximum stresses shows the existing parts and the reconstruction of the damaged parts with traditional stonework compatible with the existing it does not include stress fields that would make such an attempt problematic in terms of structural behavior. Finally, the overall study exhibits a methodology adopted that can be useful for the documentation and the restoration of numerus monuments and cultural heritage structures.

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