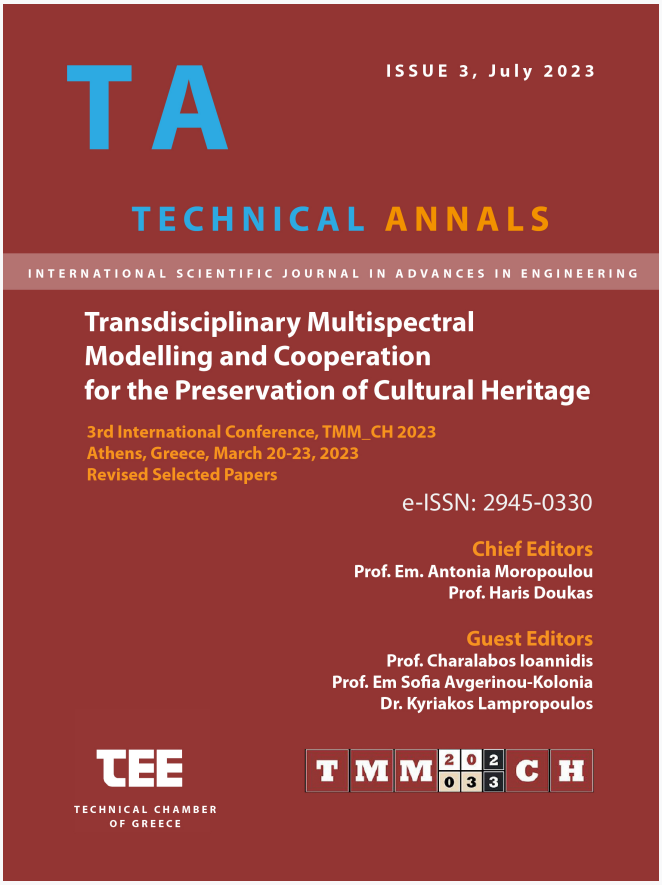
Technical Annals

Vol 1, No 3 (2023)

Technical Annals



Extensive Restorations of Arched Stone Bridges: the Examples of Plaka Bridge in Greece and Stari Most in Bosnia and Herzegovina

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doi: 10.12681/ta.34836

To cite this article:

Tzoumas, V. (2023). Extensive Restorations of Arched Stone Bridges: the Examples of Plaka Bridge in Greece and Stari Most in Bosnia and Herzegovina. *Technical Annals*, *1*(3). https://doi.org/10.12681/ta.34836

Extensive Restorations of Arched Stone Bridges: the Examples of Plaka Bridge in Greece and Stari Most in Bosnia and Herzegovina

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Abstract. In the last thirty years, Europe has experienced two major destructions of important monuments of its cultural heritage. They are both related to the collapse of stone-built, arched bridges, which were closely linked to the history and evolution of the bridging areas.
In 1993, the historic Mostar Bridge (Bosnia and Herzegovina), built in 1566 by the Ottoman architect Mimar Hajrudin, almost completely collapsed, bridging the Neretva River. The cause of the collapse was the relentless bombardement of Mostar during the Yugoslav war (1992-1995).In 2015, the entire central arch and almost 90% of the eastern pier of Plaka Bridge in Tzoumerka collapsed, following extreme weather events and a rise in the level of the Arachthos River. The bridge was erected in 1866 by master builder Kostas Bekas. The restoration of these bridges were complex, high-tech projects, and posed great challenges, being global innovations.
This article gives a brief presentation of the two bridges, and analyzes the administrative and technical framework for their restoration. The purpose of this article is to compare and evaluate common and non-common features of the two projects, since the innovative ways of restoring them can be methodological models for the restoration of similar structures.

Keywords: Arched Stone Bridge, Masonry Structure, Monument, Procedure-Framework, Restoration.

1 Introduction

A wide variety of arched stone bridges have been documented in the Balkan Peninsula, built mainly in the 18th and 19th centuries or even earlier [1]. More than 500 characteristic examples of such historical structures have been recorded just in the Epirus Region of northwestern Greece [2]. They were erected from local building materials [3] during the pre-industrial era, in order to overcome important communication and transportation obstacles. The relevant bridges often became points of reference for the areas they served. In this way, they were intertwined with the local traditions of the people, constituting great witnesses of the history and the eternal evolution of the lives of their inhabitants.

Some of these bridges exist as cultural heritage monuments in a local or supra-local level. While many of the elements of the world's cultural heritage are at high risk of destruction due to natural processes and human activities, many of them have already been destroyed especially in recent years.

Related structures are subject to a number of interdependent wear factors. The change in loading conditions throughout their lifetime [4] is a key risk factor for maintaining their structural integrity and in some cases requires appropriate measures for their preservation [5]. Deterioration of bridge construction materials, due to natural aging and wear mechanisms [4], in some cases exacerbated by the use of incompatible restoration materials, is an issue that needs to be considered, as building materials are interrelated with conservation status and response of the structure as a whole. Climate change also plays an important role in the degradation processes, as extreme temperature changes as well as extreme rainfall greatly affect and accelerate the progressive degradation of building materials [5], especially considering the wet environments in which bridges are built, receiving (extreme many times) seasonal fluctuations in river flows. Also, the destructive fury of man can be an additional factor of deterioration.

Research related to the conservation of historic arched stone bridges is on the one hand, of utmost importance for their preservation as cultural assets, and on the other hand, it proves to be significantly difficult, as each one of them is unique. Features such as: the number of arches and their shape, the dimensions of the arch and the piers [4], the building materials and the filling materials used [6], the construction method and the differentiation of construction techniques depending on the building period and region, the characteristics of the river, the environmental conditions of the area they bridge and the loads they have to carry [5], contribute to this. For this reason, it is necessary in many cases of preservation of similar monuments to apply an interdisciplinary approach [7], which will integrate and merge data from more than one field of research interest. Usually a multidisciplinary team, to be determined in relation to the type and scale of the operation, should work together from the first steps of a restoration project [8].

In 1566the construction of the single-arch, stone-built bridge Stari Most in the city of Mostar (in Bosnia and Herzegovina) was completed, which spans the Neretva River. Exactly three hundred years later, in 1866, the Arachthos River (in Epirus, Greece) was bridged, at Plaka, similarly with a stone-built single-arched bridge.

Plaka Bridge in Ioannina (after the collapse of the Korakos bridge) is the largest single-arched bridge in the Balkans, designated by the Greek State as a historical monument (1971) and a work of art “in need of special protection” (1972). The Bridge of Mostar (Stari Most) was included in the list of world cultural heritage monuments by UNESCO, one year after its restoration (2005).

Both bridges suffered significant losses for different reasons. Plaka Bridge (Fig.1) collapsed in a significant part (Fig.2), on February 1, 2015, after heavy rainfalls in the area.

Fig. 1. Plaka Bridge (downstream view), August 2014.

Fig. 2. Plaka Bridge (downstream view), May 2015.(Image source: © Ch. Giannelos)

Stari Most (Fig. 3) was destroyed on November 9, 1993 (Fig. 4) due to bombardement by Croatian forces, during the war in Yugoslavia.

Both bridges have for different reasons each, great importance for the local population and beyond. Since Plaka Bridge is not just a monument of cultural heritage and popular architecture. It is a symbolic element intertwined with historical events of Greece. Its significant size and the particularity of its construction make it a high-tech work, while its overall image and its relationship with the special beautiful natural landscape that surrounds it, and contribute to its characterization as a work of art with

artistic and aesthetic value [7]. While Stari Most was designated by UNESCO as a World Heritage Site not only because of its architectural value but also because of its great symbolic importance for the multinational community of Mostar [9].

Thus, in both cases, it was decided to restore the bridges, which has been successfully completed.

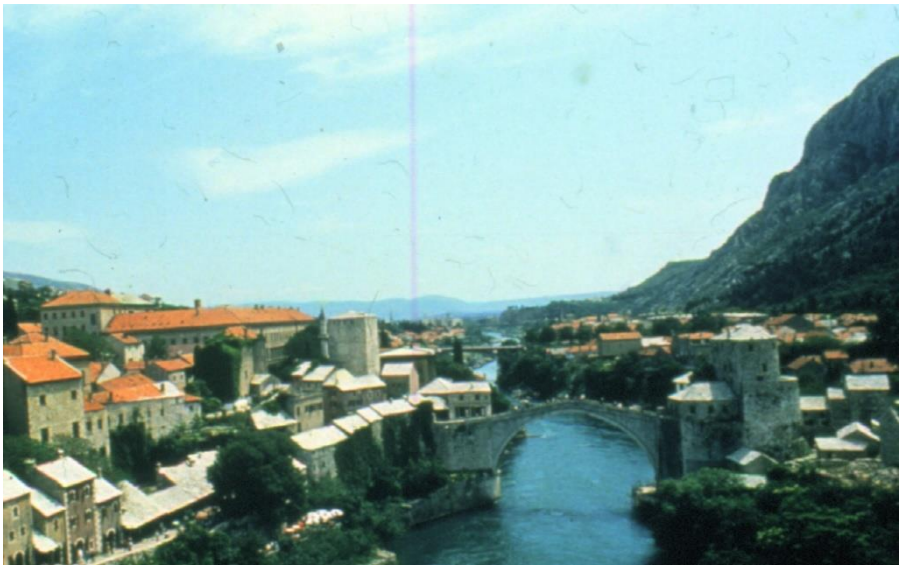

Fig. 3. Stari Most complex before the bombardement, August 1989. (Image source: © A.Pašić)

Fig. 4. The surviving abutments of Stari Most after the bombardement, December 1993. (Image source: © A. Pašić)

The restoration of the two bridges, apart from being an important technical work, raised the theoretical issue in relation to the correctness (in terms of the accepted principles of restoration) of reconstructing a large part of them. This matter was dealt with in both cases in the same way, given the great importance (from a historical, social, political, religious point of view, etc., as the case may be) of the two bridges.

For both bridges, their restoration was decided and carried out following precisely the historical structural system and using practically the same structural materials.

Despite their differences, both projects are complex and required the synergy of many factors to be carried out. Indeed, for the restoration of Plaka Bridge, three Ministries collaborated (Ministry of Culture and Sports-MoCS, Ministry of Infrastructure and Transport-MoIT and Ministry of Economy and Development-MoED), the National Technical University of Athens (NTUA), the Epirus Region andt he Municipality of North Tzoumerka, the Technical Chamber of Greece/Department of Epirus (TCG/DE), two Contracting Companies and at least four Research Offices [10].

The restoration of Stari Most bridge complex was made possible thanks to the cooperation of the city of Mostar, UNESCO, the World Bank, the World Monuments Fund and other donors (states and institutions). Among the donor countries are Italy, the Netherlands, Croatia and Turkey. Also, the European Union (through the Council of Europe Development Bank), the World Monuments Fund (WMF) and the Aga Khan Foundation for Culture [11].

The loss of the two bridges over a large area, allowed the exhaustive documentation of the monuments, which contributed to their scientific restoration.

In this paper, administrative and technical issues are presented, which were a necessary and important factor in the success of these complex projects and concern the framework, methodology and cost of the restorations.

Through the presentation of the restoration projects of the two bridges, as well as through the comparison of the procedures followed, it is possible to draw essential conclusions regarding large-scale interventions in cultural heritage structures.

The methodology followed in this work is related to a bibliographic research regarding the context of restoration of Stari Most, while regarding the project of the Plaka Bridge the author of this text was directly involved in the restoration, due to his position (routing of the commissioning process and project supervision).

2 Plaka Bridge

2.1 Brief description of the bridge

Plaka Bridge is geographically located in the settlement of Raftanaioi, of the Municipality of North Tzoumerka, of the Regional Unity of Ioannina. It was part of the road network connecting Tzoumerkochoria with Arta and Ioannina, and the old Municipalities of Pramanta with Katsanochoria (Fig.5), which are separated by the Arachthos River very close to its confluence with the Raftanitikos stream.

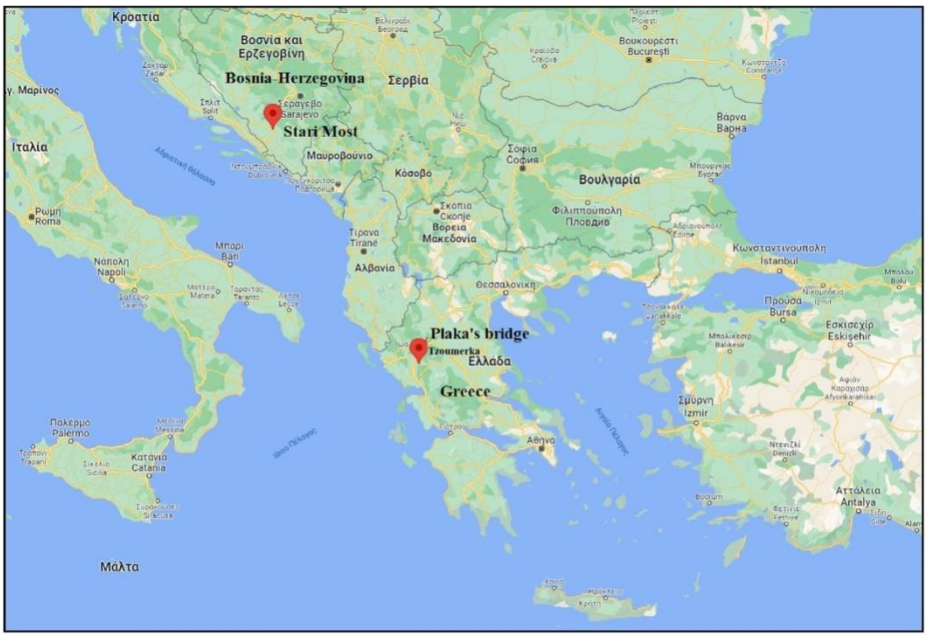

Fig.5. Positioning Plaka Bridge and Stari Most. (Image source: © google.com/maps)

Plaka Bridge is the largest single-arched bridge in the Balkans [10]. It has been designated as a work of art in need of special protection[1] and has been declared as a historic preserved monument[2].

After the initial failed attempt in 1863, the bridge was rebuilt in 1866 by the Tzoumerkioti master builder from Pramanta, Kostas Bekas [12], and was preserved until 2015 (Fig.1). The bridge worked beneficially for the people of Tzoumerka, since it was a vital necessity for the commercial communication of the region with Arta, from the time of its construction until 1881, the year in which most villages in the region gained their freedom from the Turkish yoke, after their annexation to the Greek State [12, 13], according to the Treaty of Berlin.

It consists of the central arch (Fig.1 and Fig. 11) that has a free opening of about 40m, a height of about 20m and two false-arches, the eastern arch with an opening of 6.6m and the western arch with an opening of 5.2m. The total length at the level of the parapets is 72m. Its width is 4.5m on the eastern and 5.0m on the western pedestal, decreasing progressively towards the piers, remaining constant only along the central arch, which is 3.7m wide at its bottom.

The central part of the bridge consists of two arches: the main (interior) and the second (exterior) which is built above the main. The construction is of very good quality

[1]With Decision no. 22676/17.2.1971 (Government Gazette 162/B΄) of the Minister of the Presidency of the Government.
[2]With Decision no. 10062/934/12.7.1972 (Government Gazette 621/B΄) of the Minister of Culture and Sciences.

with slab-like, roughly hewn stones, 9~12cm wide and their average weight is 80kg. The thickness of the joints is exemplarily very small 3~7mm [7].

In the main arch, around 450 worked vault stones appear in each arch, similarly in the auxiliary and eight times more stones (but smaller) in the thickness between the two sides. The total number of stones in the main arch is estimated at approximately 9,000 pieces. The rest of the structure contains about 12,000 fine stones on the surface, while ten times more were the stones of the inner filling. The stonework had a volume of about 1,500m^3, of which 300m^3 was only for the central arch, the weight of which amounted to 4,000 tons together with the parapets and the deck [7].

Apart from the stones and mortars, the structure contained a large amount of timber, formed into superimposed lattices and two systems of metal reinforcements [transverse system (arpizes) and longitudinal system of metal links][7].

2.2 The Collapse of the Bridge

On February 1, 2015, the largest part of Plaka Bridge collapsed, after heavy rainfalls and a large rise in the water level in Arachthos River, due to extensive scouring of the eastern pier [7, 14]. It completely collapsed the central arch and almost 90% of the eastern pedestal (Fig.6).

Fig. 6. Surviving sections of Plaka Bridge, September 2018. Left: part of east abutment and the Customs building. Right: West abutment and piers body.

The investigations carried out by the scientific staff of the NTUA included - among others - the architectural documentation of the bridge, the documentation of the supporting body (including the structural materials and the wooden and metal elements which were easily identified and recorded due to the collapse) and the study of its pathology [7].

A geotechnical survey, investigation of the hydraulic elements of the river, as well as numerical simulation and analyzes of the monument were also carried out. All these elements, which confirmed the sufficiency of the integrity of the bridge against the actions exerted on it and gave a convincing explanation in principle for the causes of

its collapse, served as the basis for taking - from a technical point of view - the decision to restore it.

The main cause of the collapse was the undermining of the foundation of the eastern pier [7, 14].

2.3 Procedures of the Administrative Framework of Rehabilitation

After the collapse (2015) and until the completion of the restoration of the bridge (2020), actions were implemented both by the central and regional administration, as well as by the local government, with the assistance of the NTUA, as well as technical companies. The following is a summary calendar of the main relevant actions and decisions:

- On February 5, 2015, an autopsy was carried out by a scientific team of the NTUA and a meeting in the Region of Epirus. The condition of the bridge was ascertained and preliminary proposals were formulated for its restoration.
- On February 18, 2015, a Project Group was formed by the NTUA to study the restoration of Plaka Bridge.
- On August 10, 2015, the 1st Programmatic Cultural Development Agreement (PCDA) was signed, for the implementation of the preliminary works of the restoration, with the MoCS, the Region of Epirus, the Municipality of North Tzoumerka, the NTUA and the TCG/DE as parties. The Region of Epirus was designated as the implementing body and the subject of the contract, among other things, was the work of retrieving the fallen sections and the work of strengthening the surviving sections of the bridge. The 1st PCDA was implemented in three phases and was completed on July 13, 2018.Part of the work and research of the 1st PCDA was carried out with the sponsorship of the company "Terna SA", which provided the necessary equipment and technical staff. The company "Kalliergos OTM SA" prepared the Foundation Study of the Eastern Pier.
- On July 11, 2016a Decision of the Minister of Culture was issued approving the specifications and directions for the restoration of the Bridge.
- On June 15, 2017 the 2ndPCDAwas signed for the implementation of the project "Fastening, Restoration, Rehabilitation, Highlighting of the Arachthos Bridge in Plaka", with the MoED, the MoCS, the MoIT, the Region of Epirus, the Municipality of North Tzoumerka, the NTUA and the TCG/DE.
- The object of the 2ndPCDA was the restoration of the bridge, its protection from the local erosion of the river, the shaping of the surrounding area, the restoration of the landscape and its promotion, in order to enable the integration of the monument into cultural, social and economic life of Epirus, to contribute to the preservation of the architectural memory-history of the region and to be an important pole of attraction for getting to know the place and its history.In order to deal with special scientific issues of the PCDA, an eleven-member Scientific Committee of the Project was established under the responsibility of the NTUA.
- On January 31, 2018 the Minister of Culture & Sports, with her Decision, approved the studies of the project, which were prepared by the MoIT (Directorate of Road Infrastructure) with technical consultants Kalliergos OTM SA and Ch. Takos.

- On September 18, 2018 the relevant contract was signed and the implementation of the project was undertaken by the construction company Nirikos Techniki SA. The cost of the project, including all studies, as well as the costs of the two PCDA's, amounted to €6,150,000.00 [10].
- On August 18, 2020 the restoration of the monument was completed.

2.4 Rehabilitation Framework

The restoration project of Plaka Bridge was complex, high-tech and the first (almost) complete restoration of a work of art and a listed monument in Greece.

The interventions related to the purely technical part of the restoration framework, in general, were the repairs and reinforcements of the surviving sections, the restoration of the sections that fell in February 2015 and general works on the deck, parapets and the surrounding area, which had directly related to the bridge.

The basic planning principles for the interventions emerged from the NTUA Project (2016), as approved by the Central Council of New Monuments (CCNM), were harmonized with the decisions of the Scientific Committee and are related to [7]:

- the performance of the initial engraving of the bridge with the shaped parapets and without the unintended deformations noted during the life of the bridge, according to the restoration study,
- the similarity to the historical structural materials,
- the maintenance of the historical construction method, but with different auxiliary means (molds-scaffolding) and
- the preservation of the metal links and application of wooden eschars, for historical reasons.

2.5 Restoration Methodology

The restoration work of the bridge (2ndPCDA) was divided into seven groups [10]:
Group 1. Execution of preliminary works of Western Access.
Group 2. Restoration of Western Access.
Group 3. Execution of preliminary works of Eastern Access.
Group 4. Restoration of Eastern Access.
Group 5. Restoration of Central Arch.
Group 6. Work to complete the restoration of the Monument.
Group 7. Retrieving a fragment of the collapsed arch from the riverbed.

The subject of the 1st and 2nd group was related to the implementation of the preliminary works and the restoration of the western access, while the 3rdand 4thgroup were related to the implementation of the preliminary works and the restoration of the eastern access. Based on these, all the necessary works were carried out, which related both to the preparations for the implementation of the main restoration works of the bridge accesses, as well as the works related to the realization of the restoration of the eastern and western access.

Thus, in the context of group 1 and 3, works were carried out such as: a) installation of a trigonometric network around the perimeter of the bridge, b) application of the arrangements of the river course and waterproofing and protection measures on a case-

by-case basis, c) cleaning of the existing stonework from plants and deforestation of trees and bushes at the edges of the accesses, d) installation of a system for monitoring movements and measuring the width of cracks, e) construction of the piles and the header support of the formwork and f) construction and installation of the mold and its support scaffold.

In the context of groups 2 and 4, works were carried out, indicatively, such as: a) removal of the upstream parapet and part of the deck in the area of the western arch, as well as old grouting of the surface of the walls, b) sealing of wall cracks and the salvaged part of the arch with grouting and new grouting of their surfaces, c) restoration of western abutment walls in contact with the rock and construction of the trunk of the eastern pier, with the corresponding part of the springing line of the central arch, d) repair of spandrel walls and construction of the filling material between the spandrel walls of accesses, e) restoration of the base of the deck, f) repair of the wing wall of the western pier and g) installation of transverse system.

The 5th group, most important from a technical point of view, was the guide of the restoration of the central arch of the bridge. Within the context of the group in question, the pales and the pale cap of the central arch mold were manufactured. The mold and its support scaffolding were installed.

The 6th group was related to general works to complete the restoration, while the 7th group was related to the retrieval of a large fragment of the collapsed arch from the river bed.

2.6 Restoration Materials

According to the Scientific Committee, the new structural materials had to be as close as possible to the historical materials [7]. In addition to the stones, mortars and grouts as well as the metal elements that were incorporated into the project, chestnut wood was used.

- Stones. The NTUA scientific team proposed to use generally stones from the same rock as that of the historical structure, which is found in the wider area of the bridge [7]. The restoration study of the monument suggested that, under certain conditions, some of the stones of the historical structure that fell and were collected could be used in the internal filling of the bridge or in sections without much stress. Based on the architectural documentation study, the use of three types of stones was foreseen: flagstones, masonry stones and porolits [15]. Finally, the stones from which the bridge was built came from a quarry in the Dafnoula area of Ioannina [10].
- Mortars – grouts. For the mortars, since it was not possible to apply them exactly the same as the historical ones, compositions with similar physical characteristics were proposed by the NTUA [5, 16], confirmed by the MoCS(Directorate of Research and Technical Support of Restoration Studies and Projects) [17] and adopted be the MoIT (Directorate of Road Infrastructure), fulfilling the requirements of developing the desired strength in a reasonable time. Because the location of the operation is heavily stressed by the flow of the river, the choice of mortar and grout was based on the rapid development of high strength and high durability. Lime-pozzolan compositions were provided for mortars and grouts.

For crack grouts, lime-pozzolan compositions combining rapid hardening with better cohesion were considered [5, 16, 17].

- Metal elements. As mentioned above, the specifications set for the restoration required the preservation of the metal links (transverse and longitudinal) of the historical construction. Two types of metal reinforcements were applied to the bridge, in the piers and in the central arch [18].
  Industrial steel was used in the historical construction of the piers. Transverse metal connectors (*arpizes*) were used on the inner part of the central arch of the bridge. For wedging the anchors, nails with curved ends (*giftokarfa*) were sometimes used [18, 19].
  The new metal elements installed on Plaka Bridge were titanium, which was used for the construction of the arpizes, as well as stainless steel, which was used for the construction of the metal grids, the metal links of the eastern pier and the metal trusses [10]. It was not possible to re-use lead in the anchor holes and simultaneously reuse the best-preserved links.
- Wooden elements. The wooden grids of the historical construction, which were preserved during the restoration, are divided into two categories: horizontal and radial grids [18, 20]. From the fallen fragments, but also from the salvaged part of the western arch in which the holes are preserved in the positions of the now disintegrated timbers, the existence of four horizontal eschars was documented [18, 20]. The horizontal grids were made of fir wood, while the radial grates of oak wood. The material used for the construction of the new grids is chestnut wood.

3 Stari Most

3.1 Brief description of the bridge

Stari Most (Old Bridge) built at an altitude of about 60m, is geographically located in the southeast part of the city of Mostar (Fig.5), which owes its name to it. On both sides of the bridge rise its towers, called Mostari, i.e. guardians of the bridge. It stretches over the Neretva River and connects the Bosnian-populated eastern part of the city with the Croat-populated western part. For centuries it has been considered a symbol of bridging the East with the West, not only the Christian world with the Islamic world but also the Catholic Croats with the Orthodox Serbs. Today, the reconstructed bridge is a symbol of reconciliation, international cooperation and of the coexistence of diverse cultural, ethnic and religious communities [11]. While, locally it has become a symbol of pride and identity for the people of Mostar [21].

The bridge was built in 1566 [9, 22, 23] by Mimar Hajrudin, the disciple of the Ottoman architect Kodza Mimar Sinan [24], by order of Sultan Suleiman the Magnificent. Stari Most built in the Ottoman era went through many changes and renovations. Most modifications took place in the period following the fall of the Turkish Empire [25]. According to the records kept in the Sarajevo National Museum, the construction of the Old Bridge started in 1557 and was completed nine years later [25]. The chronological information about the beginning and end of bridge construction work cannot be considered fully reliable as historic records with different data are also available.

In addition to the bridge, the Stari Most complex also includes a set of buildings consisting of three towers, two mosques and other medieval structures (Fig.8) [11].A crossing already existed at this location in Mostar before the Otoman Empire, as confirmed by archeological investigations during which authentic remains of a wooden bridge were identified [9, 25].

On July 15, 2005, the bridge and the neighboring historic buildings were classified by UNESCO as a world heritage site, not only because of their architectural value but also because of their great symbolic importance [11].

The bearing arch (Fig.3 and Fig. 12), which is the most important part of the bridge, has the form of a humbled semicircle and is sharp-edged. Its total opening on the upstream side is 28.71m, while on the downstream side it is 28.62m. Its width ranges from 3.95 to 4.05m and its height is 12.06m [25]. The height from the lowest (dry) level of the Neretva River ranges from 19.0.m to 21.00m and the curvature of its interior is almost circular. It consists of approximately 1,100 pieces of stone. None of the stones used had the same dimensions. The dimensions of the average of these are: 0.40m x0.80m x1.00m [24].

3.2 The bombardement of the Bridge

The bridge was destroyed 10 days after the second siege of Mostar by Croatian forces, which began on 9 November 1993 during the 1992-1995 war in Yugoslavia [26].

According to the finding of the International Tribunal for the former Yugoslavia "the bridge was intentionally destroyed by the Croatian Defense Council"[3] and the bombardement of the bridge was seen as a symbolic act of ethnic cleansing in multi-ethnic Bosnia and Herzegovina [9].

A temporary suspension bridge was built in the place of the historical bridge after the end of the war, in order to restore the communication of the areas of Mostar on both sides of the river (Fig.7).

3.3 Procedures of the Administrative Framework of Rehabilitation

The government of Bosnia and Herzegovina requested in 1998 from the international community the financing of the rehabilitation. The following is a summary calendar of the main actions of the restoration project:

- On July 13, 1998 UNESCO, the World Bank, the World Monuments Fund and the Aga Khan Foundation for Culture entered into a partnership to oversee the restoration work.

  According to the Commission for the Preservation of National Monuments of Bosnia and Herzegovina, the cost of the project amounted to approximately 15million euros[4]. The provision of resources from various sources is as follows: 4million came from a World Bank loan to the aforementioned partnership.

[3]Indictment of the International Criminal Tribunal for the former Yugoslavia (www.icty.org/x/cases/prlic/ind/en/prl-ii040304e.htm).

[4]See also The World Bank: Document of The World Bank, Implementation Completion Report No. 32713, June 22, 2005. Bosnia-Herzegovina Cultural Heritage Pilot (2005).

7.6million collected as donations from Italy (3million), the Netherlands (2million), Croatia (0.6million), Turkey (1million) and the Council of Europe Development Bank (1million). The city of Mostar invested 2million in the bridge restoration project [11].

- On April 17, 2000 the preparation of the required restoration studies begins, which were completed in 2001. The design of Stari Most was developed in 2000 and 2001. Step by step, the design documents, the drawings and the calculations were checked and approved by an International Commission of Experts, named ICE [27].

  The control of the project, from a scientific point of view, was assigned to an international group of expert scientists, under the auspices of UNESCO, in order to ensure the historical correctness, integrity and coherence of the project. The implementation of the project was undertaken by the Turkish company "ER-BU Construction & Trade Collective Company of Ankara", which bid less in an international tender. The supervision of the works was conducted by the private company Omega Engineering, based in Dubrovnik [28].
- On June 7, 2001 took place the start of restoration work.
- On July 23, 2004 took place the official reopening of the bridge.

Fig.7. View of the temporary suspension bridge, February 1995.(Image source: © A. Pašić)

3.4 Rehabilitation Framework

The restoration project was complex and particularly difficult, since it consisted the first (almost) complete restoration of a stone-built bridge worldwide.

The restoration involved actions ranging from saving the historical parts of the bridge, researching the historical materials, defining the final restoration plan, to the final reconstruction and preservation of the structure [23].

The design, performed in a period of almost one year time, allowed keeping the structure unchanged for what concerned the construction materials, the construction techniques and the exact geometry, "even if characterised by ordinary irregularities" [25].

There were many companies and institutions involved in the preparation of research, preliminary and final studies for the reconstruction of the historic bridge complex. Among them are included both the Italian company "General Engineering WorkGroup" which prepared the Architectural Documentation Study of the Bridge, and the Department of Civil Engineering of the University of Florence which prepared the Static Rehabilitation Study as well as the Hydraulic Study (www.mostarbridge.org; structurae.net/en/structures/mostar-bridge).The German company "Landesgewerbanstalt Bayern-LGA Historical Bridges Group" was responsible for defining the new structural materials [25].

The project of the monumental restoration of Mostar concerned the restoration of the historical bridge complex and in particular the restoration (Fig.8): a) the bridge itself, b) the Tara tower, the smaller Herceguša tower, the mosque of Sultan Selim and two buildings of trade, on the east bank of the Neretva River and c) the Halebija tower, the outpost (Caradak) and a commercial structure between the tower and the bridge, on the west bank.

The fact of the total destruction of the central arch of the historical bridge made possible the archaeological investigation, including its architectural documentation through the recording of its structural details.

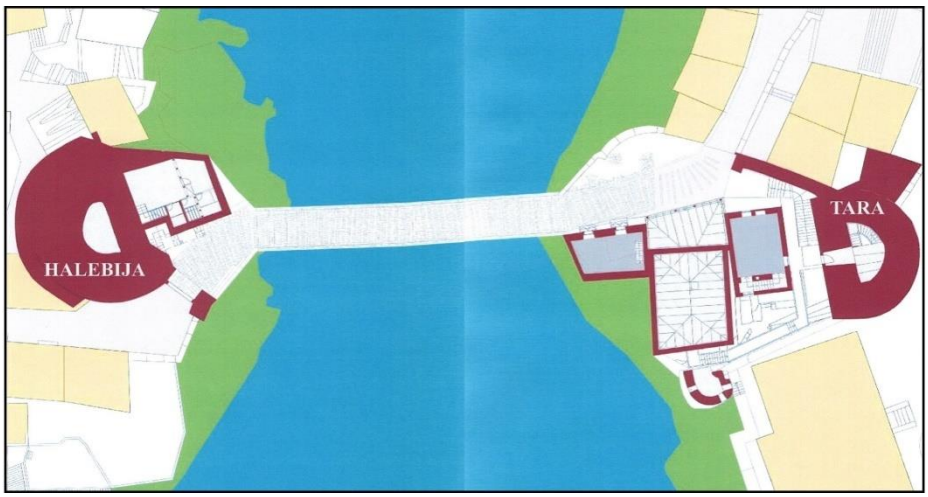

Fig.8. View of the bridge complex.(Image source: © A. Pašić)

3.5 Restoration Methodology

The bridge restoration process was divided into eighteen Phases. The order of implementation of each of them was strict and the most important of their tasks are related to [25, 29]:

- The temporary reinforcement and stabilization of the salvaged walls.
- Partial removals-deconstructions of the salvaged parts of the bridge and deck with detailed documentation and numbering of the deconstructed parts.
- The erection of a metal structure to support the construction of the arch, during which work was carried out to support the scaffolding and temporary bridging with a float.
- The assembly of the wooden mold.
- The construction of the arch and the keystone installation. The arch is structured by 111 rows of mudstones with a depth of 3.95m (from 3.92 to 3.97m) and a height of 0.80m. Each row includes 2 to 5 arch stones (average row is 3 to 4). The total number of arch stones of the arch amounted to 456 pieces and their total volume amounted to 145m^3.
- The construction of the intermediate reinforcing masonry, with the parallel construction of the lower cornice and the side spandrel walls.
- The decentering of the arch.
- The completion of the construction of the spandrel walls and the dismantling of the scaffolding.
- The construction of the upper cornice and parapets.
- The waterproofing of the bridge using a suitable type of mortar which also formed the basis of the deck floor in combination with the construction of new ones and the reconstruction of the historical elements of the deck.

3.6 Restoration Materials

A main requirement of UNESCO was the use of authentic materials and construction techniques whenever possible. That is, a new project had to be implemented, the same in every detail as the old one. Thus, the bridge was restored in a way identical to the way the historical one had been constructed. Although the construction was made with new materials, there was a significant percentage of incorporation of the historical materials.

- Stones: From August to November 21, 1997, UN forces in Bosnia and Herzegovina recovered stone sections of the damaged bridge from the Neretva River [11]. From the total of 456 arch stones, 162 pieces were recovered from the river, 24 pieces of stones from the cornice, 44 pieces of stones of the spandrels and 19 pieces of stones of the parapet were also recovered [27].

  It is a fact that the architectural beauty of the monument is due to the sophisticated plot of large and different sized stone elements with thin joints, 5~8mm thick, which were extracted from a quarry in the area south of Mostar called Mukoša [24]. Most of the stone elements of the bridge, such as the arch, cornices, spandrels and parapets were constructed from tenelija rock (Category I), which is a local oolitic limestone [22, 24, 25]. The deck and stone slabs above the cells were

constructed with hard, calcareous and light colored marble with the local name krecnjak [9].

- Mortars – grouts. During the restoration, mortars of different types and compositions were used throughout the structure, which had increased elasticity and sealing characteristics. The mortar used as a foundation was a mixture of hydrated lime and sand from the Neretva River. For the composition of the mortars were also used: artificial pozzolan, hydraulic lime, mineral aggregates and water [23, 25].

  After the completion of the restoration works of the external rescued walls, remedial works and works of grouting the cracks of the internal walls were carried out. Grouting was implemented both in the wing walls and in the rocky foundation of the bridge. The grouting was implemented by pressing limestone grout (lime emulsions). The purpose was to strengthen the walls by reducing the internal cavities created over the years, ensuring better contact with the bearing layer [25].
- Metal elements. The stone elements of the bridge were strengthened through the use of metal connectors made of forged iron, and were placed at the level of the connecting joints following different assembly methods. The metal connectors had flared ends and after their installation, molten lead was poured into the slots to finalize their assembly. The railing was similarly constructed of wrought iron [23]. The total amount of molten lead with which the arch was "reinforced" amounted to 30 tons, which was 10% of the total weight of the arch of 300 tons [25]. The metal connectors incorporated into the project consisted of nearly 1,700 anchorage elements [25] and 810 dowels (www.mostarbridge.org), and were applied to the stone elements through slots that were deliberately carved with their bottoms slightly widened in order to avoid disconnection.

  The metal connectors had flared ends and after their installation, molten lead was poured into the slots to finalize their assembly. The railing was similarly constructed of wrought iron [23].

  The metal elements, combined with the use of mortar, allowed for a fairly efficient connection system that was implemented extensively in the arch stones, where three different groups of links were adopted to better bind the entire structure. Most of the reinforcing metal links remain protected in the inner parts of the slots to prevent them from oxidizing.

4 Discussion

For different reasons, at different periods of time, vast sections of the two bridges collapsed and the governments of Greece[5] and Bosnia and Herzegovina immediately decided to restore them.

[5]The fact that Plaka Bridge was a cultural monument of a supralocal nature, combined with the fact that Greek society has a living relationship with its cultural heritage, led to the almost universal demand for its restoration (over 85%), and even in a period of fiscal crisis for the country [30].

The analysis attempted in this article highlights important similarities in dealing with the two projects of total restoration of stone-built bridges. The administrative framework for organizing the actions, the agencies involved, the financial object, the methodology, the prioritization of the implementation of all the required actions and the times in which they were achieved, show this conclusion in an emphatic way.

The Stari Most project was a global innovation, from every point of view. For the first time, international organizations, cultural and educational institutions, countries, and private companies collaborated to make it work in the best possible way. The restoration of Plaka Bridge was a complex, high-tech project, and was a great challenge, as it involved the first almost complete restoration of a work of art and a preserved monument in Greece. Central, regional and local administration, a university institution and the TCG collaborated on the rehabilitation procedures and framework.

The two bridges were fasten and restored to their historical form using the same stones, similar mortars and following the same methods as their historical constructions. The historical correctness, integrity and coherence of the projects were ensured for the restoration of Plaka Bridge by the Greek scientific community and management by the central administration, while for the restoration of Stari Most, by the international community of specialist scientists and management by the Unesco.

The restoration of Stari Most lasted 37 months (June 7, 2001 to July 23, 2004), while the main contract for the restoration of Plaka Bridge lasted 27 months. Both restorations were special trials because of the multi-participation, but mainly because of the deviation from ordinary. The loss of the two bridges over a large area allowed the exhaustive documentation of the monuments, which contributed to their scientific restoration.

The restoration of the bridges included many common phases: from the rescue of the historical parts, the research of the historical materials, the determination of the final restoration plan, the final restoration and also the preservation of the structures. The bridge restoration works were similar both in terms of their type and the order in which they were carried out. The reinforcement of the remaining sections, the dismantling-deconstruction of the fragile material, the setting up of the metal scaffolding and the wooden moulding, the way of building the arches, the building of the masonry, the pedestals, the process of de-arching with the necessary monitoring of the phenomenon of movements-deformations, the completion of the construction of the spandrel walls, cobblestones and parapets were implemented in a similar sequence both in Mostar and in Plaka.

The materials used in both cases were similar. The stones incorporated into the projects came from the surrounding areas. In both cases, similar to the historical ones were used, however new types of mortars-grouts, which had increased elasticity, sealing characteristics and strength. The imperfections of the historical construction as well as the deformations due to stress of the two bridges were not repeated in the restorations.

However, there are three differences between the two projects. Plaka Bridge was a more demanding project in terms of dimensions compared to Stari Most. In practice, less than 400m^3 of stones were required in total for the restoration of Stari Most, while for the restoration at Plaka, at least 800m^3 of general stones, 4,000 pieces of arch stones and 102 pieces of stone keys were incorporated into the project [10].

Also, the level of difficulty of the projects related to the field conditions was certainly higher in the Plaka area, since the work had to take place in the Arachtos River, with intense rainfalls and (almost) flooding (Fig.9). On the contrary, the location of Stari Most as well as the field conditions in Mostar favored the avoidance of unforeseen situations during the progress of the works (Fig.10).

The third difference concerns the significant percentage of incorporation of historical materials (mainly stones) in the bridge in Mostar. The differences are exhausted in the use of structural materials, a matter directly intertwined with the historical construction technique of the bridges. In the case of the bridge in Mostar the main connecting material was most the metal elements and less the masonry mortar, while in Plaka was the opposite.

Fig. 9. Conditions in the area of the restoration project in Plaka, November 2019.[6]
(Image source: ©Nirikos Techniki SA)

[6]Photo on the left comes from a surveillance camera installed on the eastern slope (upstream view), where the large elevation of the water level can be seen, and the crest of the wing wall can be seen marginally. There have been cases where the supply has "disappeared" the wing wall. Photo on the right shows a landslide of part of the eastern slope after heavy rainfalls. The upstream wing wall can be seen again, as well as the Customs building.

Fig. 10. Conditions in the area of the restoration project in Mostar, September 1997. (Image source: © A. Pašić)

5 Conclusions

The present work has shown that the implementation of projects of similar size and importance, such as the restoration of the two historical bridges, require an interdisciplinary approach in order to deal with their complexity in a more comprehensive way, but at the same time to respond the research questions posed on a case-by-case basis in a more rational way. It is also clear that the management of complex projects of extensive restorations requires the simultaneous cooperation of various agencies and organizations, in conjunction with the academic, scientific, research and technical communities.

Moreover, the restorations of Plaka Bridge and Stari Most are, by world standards, pilot projects. Both the innovative ways of restoring the bridge in Mostar and the one in Plaka can be methodological models for the restoration of similar monuments, which have suffered damage-destruction of a similar magnitude.

Plaka Bridge, built in 1866, was closely linked to the history and evolution of the place and in particular to the villages of Tzoumerka, whose inhabitants it served, contributing decisively to the survival of the local communities, in times of significant communication difficulties. It is again an elegant work of uppermost beauty that shows the technical intelligence of the old bridge builders of Epirus, being an important element of the cultural identity and life of the place (Fig.11).

Stari Most, built in 1566, has been considered for centuries a symbol of bridging the East and the West, not only the Christian world with the Islamic world, but also the Catholic Croats with the Orthodox Serbs. The restoration of the bridge in Mostar (Fig.

12) had an additional goal, to lead to the restoration of emotional bridges, between Croats, Serbs and Muslims, to the reconciliation of the inhabitants of Mostar, who are so different from every point of view[7]. The restoration of the historic bridge of Mostar is a symbol of the restoration of the country from the civil war, the reconciliation and reunification of the multi-ethnic communities and by extension the multi-ethnic and multi-religious Bosnian society [9].

Fig.11. Plaka Bridge after restoration (downstream view), August 2021.

Fig. 12. Stari Most after restoration (downstream view), September 2006.
(Image source: © A. Pašić)

[7] See also Radulovic, A.: The Question of authenticity in recoveries in post-conflict zones, In Proceedings of the 2nd International Conference on Best Practices in World Heritage, People and Communities, 29 April-2 May 2015. Menorca, Spain (2015).

Anyway, the specialized use of authentic materials, the particular morphological characteristics, their aesthetic value, as well as their importance both for the forest-rural landscape of Tzoumerka, and for the urban landscape of Mostar, they are both established as recognizable reference points of cultural heritage, and as national and international symbols and achievements of human potential.

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