Mostar Old Bridge rehabilitation

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ABSTRACT: The Old Bridge in Mostar ranks among the greatest historical monuments on the Balkans. The bridge was demolished in 1993 during military operations in Mostar. 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.
After the war the bridge was rebuilt. In this paper some of the most interesting stages in reconstruction are shown.

1 INTRODUCTION

The Old Bridge in Mostar ranks among the greatest historical monuments on the Balkans. The bridge was demolished in 1993 during military operations in Mostar. According to records kept in Sarajevo National Museum, the construction of the Old Bridge started in 1557 and was completed nine years later during the rule of Suleiman the Magnificent. The chronological information about the beginning and end of bridge construction work can not be considered fully reliable as historic records with different data are also available. According to writings of Turkish historians, the main builder was Sinan's disciple Hairudin. 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. The bridge built in the Ottoman era went through many changes and renovations, but details about such works can not be obtained due to scarcity of records. Most modifications took place in the period following the fall of the Turkish Empire.

After the demolition of the Old Bridge, the International Committee of Experts (ICE) engaged the Florence-based company General Engineering s.r.l. which prepared the design for the renewal of the Old Bridge in Mostar. The concept for building vault walls of the Old Bridge in Mostar is based on the selection of component materials resulting from analyses.

Reconstruction project of the Old Bridge is one of the greatest and most valued historical UNESCO projects in last several decades in Europe. The arch of the Old Bridge was the most important part of reconstruction. Dimensions of the new Old Bridge were accurately executed to maintain the originality of the structure. The complete process from the beginning to the finishing of the arch was unique and incomparable to any other project or structure.

In 1993 the Old Bridge of Mostar has been totally destroyed (Fig. 1) and its ruins are the only left portions that should be considered the real and original Old Bridge of Mostar. The recovered stones are valuable elements of a great ancient monument, they have historical value and they represent an interesting example of the ancient technique of assembling voussoirs and a constructive method which should be studied and investigated.

Some bridge stones and arch voussoirs that have been recovered from the river and were apparently not broken and their original position has been determined are stored.

2 HISTORY OF THE OLD BRIDGE

The Old Bridge was a continuous inspiration for architectural and structural art, paintings, musical and every other kind of art. The location of the contemporary city of Mostar is first mentioned in 1452 in the Dubrovnik archives under the name *"duo castelli al ponte de Neretva"*. This is the oldest written document about the medieval Mostar. The Ottoman Empire conquered the city in 1468 and it is first mentioned in written documents in 1477. The stone bridge was built by the local people and carvers and masons from Dalmatija.

The stone arch single span of the Old Bridge is 28.70 m the vault has constant depth of 80 cm and variable width from 392 to 397 cm. Curvature of the arch is close to a lowered centre half-circle, (with some peculiarities at the impost level and at the key stone). It was characterised by very slender and elegant shapes: its profile and its skyline were so thin and so high over the river waters that it was hardly to believe that such a structure could be worked out of huge stone blocks. Built in tenelija stone, it was of a light tone colour, bright and changing during daytime depending on sun colours.

The bridge was mainly conceived as a functional structure, aimed mostly at connecting the two banks of the river. Its design has been quite influenced by the morphology of the site which is totally matched by its abutment walls. The whole monumental complex, including the adjacent fortification towers, is totally part of the site, castled on the rocks and winding the banks, it is not the result of a single design work, but of a development during time, that has followed the historical happenings and the need for protecting and keeping the passage over the river.

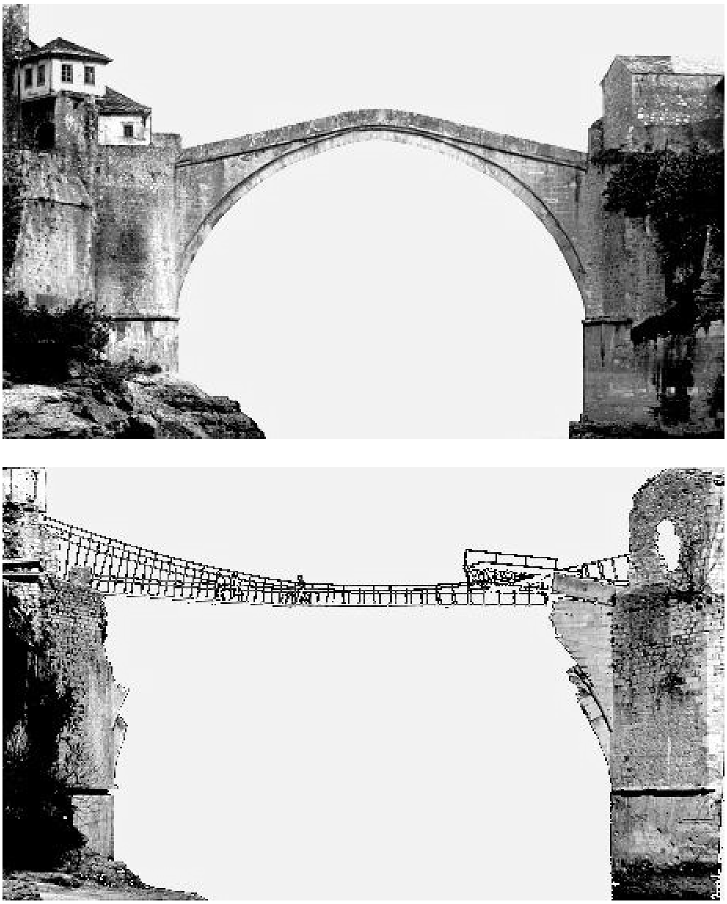

Figure 1: Old Bridge of Mostar before and after the demolition

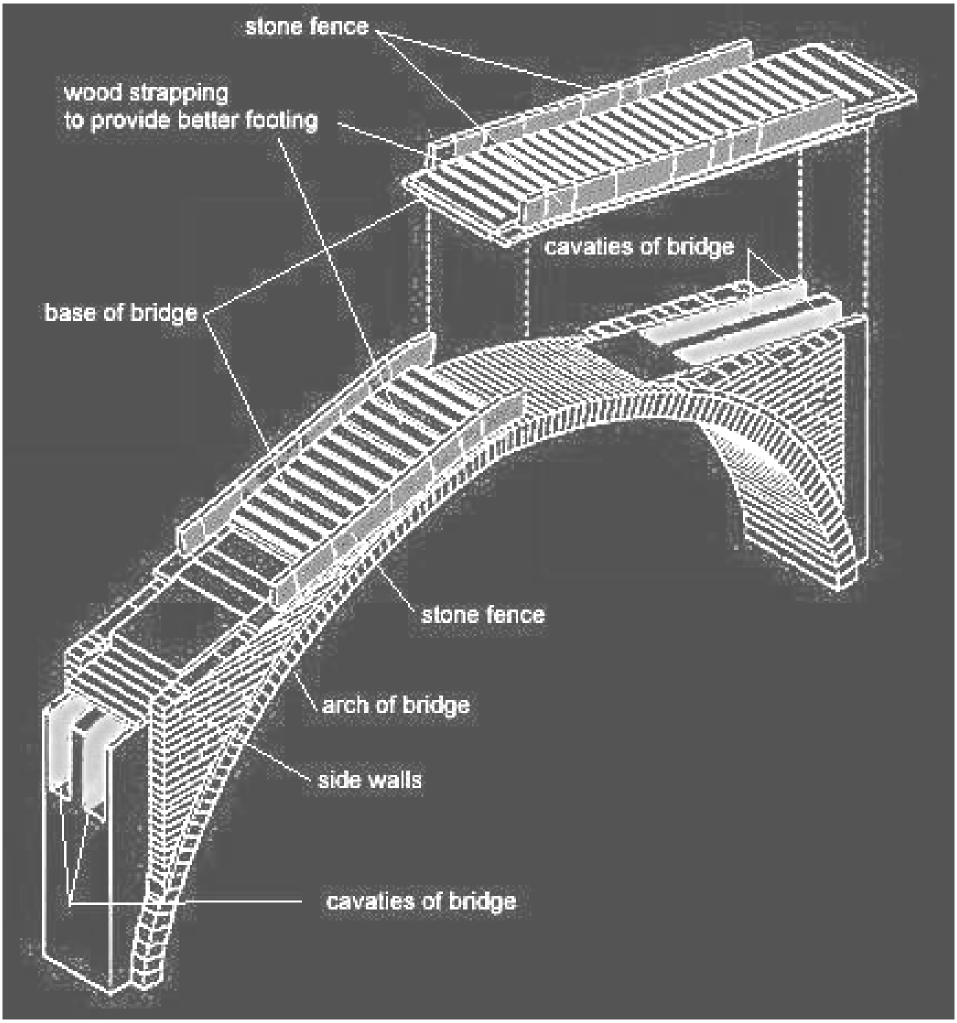

Figure 2: Old Bridge structural elements

The bridge had few esthetical devices and no ornamental element; its architectural beauty and value were to be found in the simplicity and in the essentiality of the structure (Fig. 2): the shapes of the bridge were not linked to any time, to any style and to any fashion, in a way that the bridge of Mostar has always been admired as symbol.

The arch was ″reinforced″ with 30 tons of lead built in alongside iron cramps and dowels. The lead totalled 10 % of the arch weight of 300 tons. All the stone blocks were connected in transversal and longitudinal direction. Around the cramps and dowels melted lead has been poured through a culvert in the stone at constant temperature around 390°C.

During the 1950's some reconstruction work on the arch abutment had been made in 1963 the arch has been injected and damaged stone blocks replaced and in 1982 detailed archaeological recording has been made which enabled this recent replica.

3 COMPOSITION AND PROPERTIES OF MATERIALS

The analysis of mortar used in masonry work revealed that materials from nearby localities were used during construction of the stone bridge. Basic materials for fabrication of mortar used in masonry work were sand from the Neretva River and quicklime burnt in traditional way in ″*klačina*″ which is a traditional limekiln. The description of lime burning at this kiln can be found in archives.

Crushed brick fragments, bauxite powder or terra rossa (additions with low pozzolanic activity) were also found on mortar fragments. It is assumed that organic additives in form of eggs or cheese (albumin and casein) were also used.

Old mortars used in vault wall construction have lost their initial compressive strength and durability. Masonry joints were opened and damaged.

All this was taken into account during selection of component materials for the fabrication of mortar used in vault wall construction. The selection is based on the opinion formulated by the expert group and on recommended compositions as prepared in Civil Engineering Institute of Croatia in Zagreb and Mostar.

The vault mortar is fully based on traditional (historical) component materials. The job mix formula used in the vault wall construction is composed of crushed brick, lime paste obtained by quicklime slaking and sand from the Neretva River.

The job mix formula was selected after inspection of thirty initial job mix formulas.

The mortar for masonry work is based on the SITE MADE MORTAR compliant with EN-998-2, Item 3.4.3. Component materials were added by volume and mixed together in the on-site gravity mixer.

Basic properties of mortar for the vault construction are shown in Table 1.

Table 1 : Basic properties of mortar for the vault construction

Type of mortar	Fresh mortar consistency [mm]	Water retentivity [%]	Compressive strength (samples 4x4x16 cm) after 28 days [N/mm^2]	ME [N/mm^2]
Mortar for vault wall construction	141	98	0.92	1018.78

The primary function of the mortar used for vault construction is to enable soft transfer in case of stone block displacement in the vault. That is why the mortar had to provide low ME, which was achieved.

Stone for fabricating blocks for the vault construction was extracted from the same deposit that was used for the Old Bridge, and the same traditional dressing method was applied.

The building stone locally called ″*tenelija*″ (Fig. 3), originating from the nearby Mokuša stone deposit, was used as raw material for the fabrication of stone blocks for vault construction. According to data obtained from LGA (Landesgewerbanstalt Bayern – Historical Bridges Group) analyses on all bridge materials remaining after the demolition of the Old Bridge the building stone originating from Mokuša deposit is characterized by compressive strength of approximately 20 N/mm^2, by high capillary water lifting capacity and by high initial capillary water absorption. This fact had to be taken into account during selection of mortar composition and when preparing the stone for masonry work, Masonry mortar is characterized by high water retentivity, so it is highly unlikely that it will ″burn out″ in the joint, particularly as every stone was immersed in water for 24 hours prior to placing.

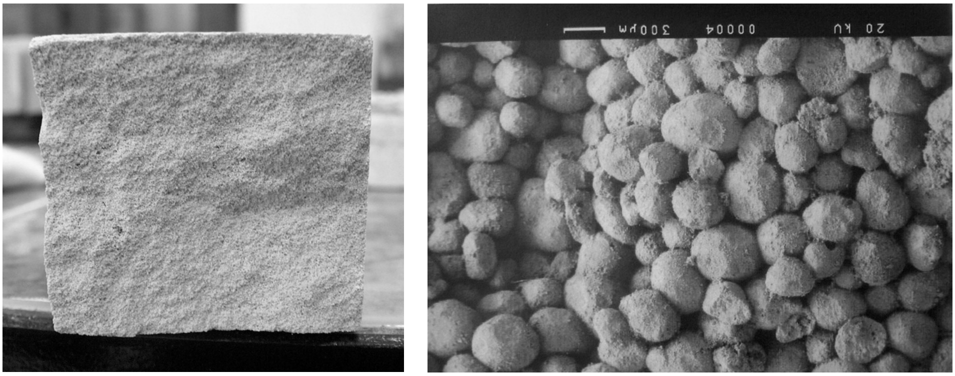

Figure 3: Temelija stone

4 STRENGTHENING OF THE EXISTING ABUTMENTS

The Old Bridge rehabilitation plans included the strengthening of the existing abutments by way of drilling grouting ports ∅56 mm more than 5 meters deep, distributed atone port per m^2 and filling them with grouting mix. Such a design was deemed to destructive and inappropriate for the existing abutments surface. The contractor proposed a more appropriate grouting technique through joints between stone blocks. These procedure required 4 to 5 narrow ports /m^2 whose depth depended on the thickness of the grouted stone wall.

After the demolition of the Old Bridge its abutments and abutment inner and outer stone wall system (Fig. 4) was left without a portion of the load from the bridge arch reactions. The stress grouting activated the horizontal component of the waterfront structure onto the bridge structure and vice versa.

At the time of the original bridge construction, waterfront walls and parts of the bridge had been built simultaneously. After the demolition the waterfront structure was still existent with reduced load while only the bridge elements needed to be reconstructed.

Archaeological excavations on the site, especially excavations of the abutment fill where some 1200 m^3 of rubble was excavated, have shown that the abutment really consists of principal abutment block, inner abutment walls of varying thickness and outer, waterfront, wing walls overlaid with cut stone.

The contractor proposition was accepted after a test area was grouted and thoroughly evaluated. Expectations based on experience with improved grouting mix flow and adhesion through use of closely spaced grouting ports have been met completely.

When the bridge masonry work has been completed and the cantering was still under the arch stressed grouting has been executed and horizontal reactions activated thus reducing the load on the cantering.

Grouting below the Old Bridge cornice level included grouting and strengthening of the wing walls with replacing damaged stones on the wall face, filling the joints and grouting the walls through the joints and strengthening the load bearing ground with grouting (Fig. 5).

The waterfront walls have been repaired by replacing damaged stones on the wall face by rebuilding portions of the missing stone blocks and by filling the joints between the stone blocks and grouting.

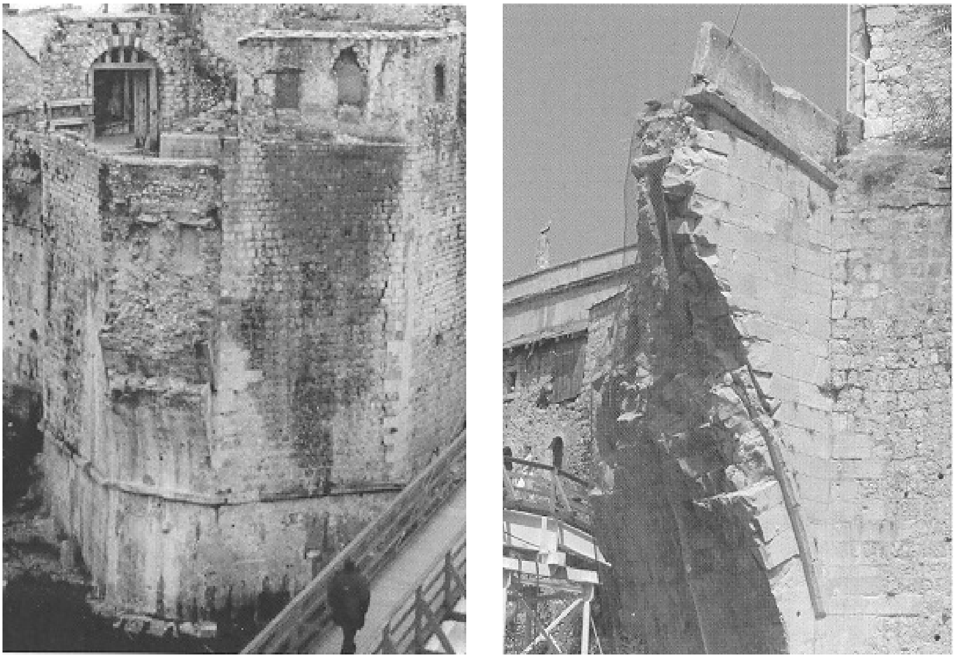

Figure 4: Before the rehabilitation – right and left bank

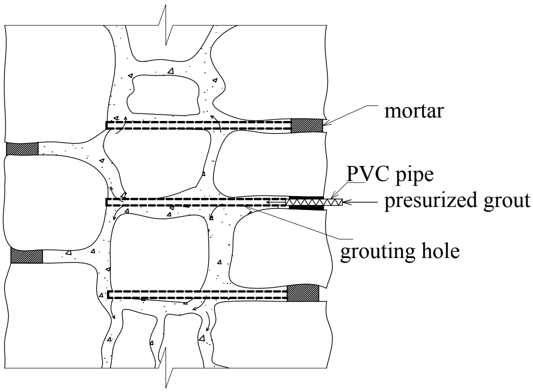

Figure 5: Cross section of the grouting holes

The purpose of grouting is strengthening the wall, reducing the number of cavities within the wall and ensuring better contact with the underlying ground. Reduction of the number of cavities in the wall was necessary for achieving reduced permeability of the wall thus preventing grout creeping while grouting the ground behind the wall.

The procedure included cleaning the joints between the stone blocks, replacement of damaged stones and rebuilding the wall sections where the stone blocks were missing upon which the joints were sealed with limestone mortar of colour and composition approved by heritage conservation office.

Once the mortar in the joints hardened 16 mm wide grouting ports were drilled and grouting pipes were put in place. Since the wall grouting had to be carried out on one side only, the depth of the grouting ports has been made equal to the wall thickness. Inspection of the walls has shown that the wall thickness is between 60 cm and 80 cm (Fig. 6).

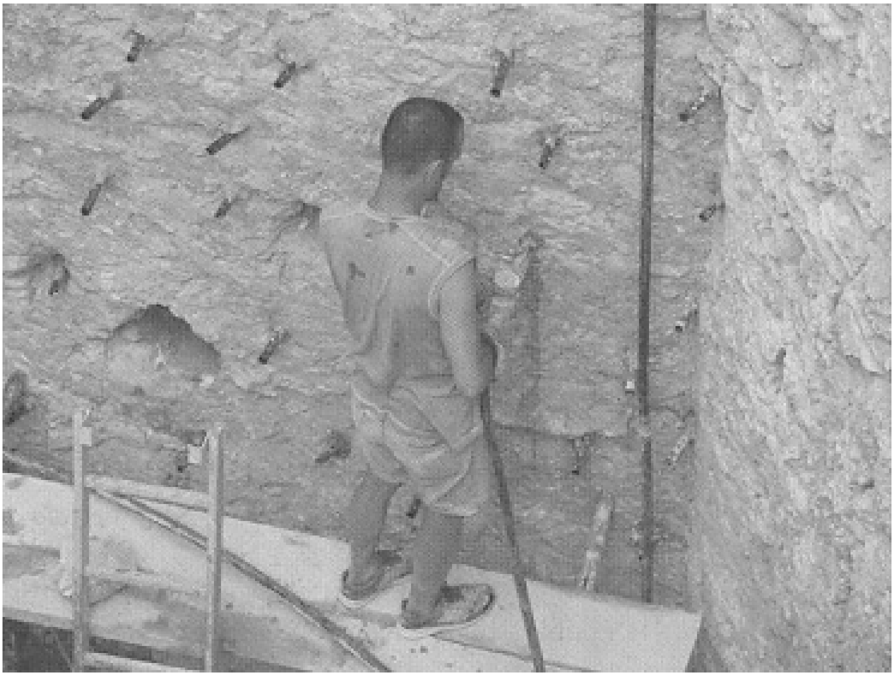

Figure 6: Stone abutment grouting

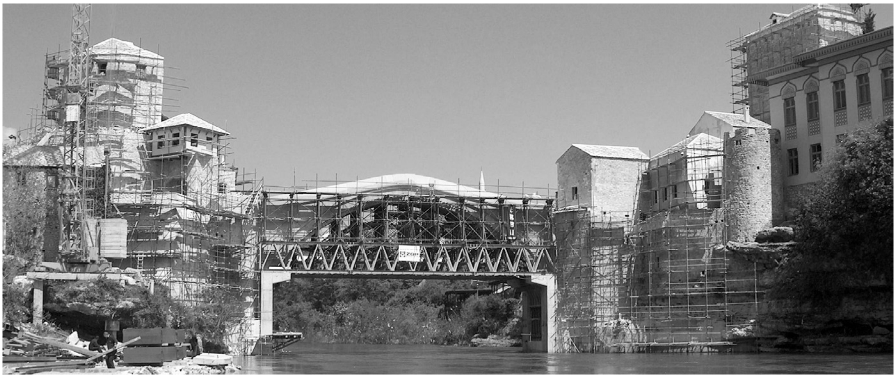

Figure 7: Construction of the Old Bridge

Grouting was carried out with an industrial lime-based grout. Grouting holes were placed at each horizontal joint. The number of holes per m^2 varies depending on the spacing of horizontal joints and stone block size, but generally there were 4 to 5 holes/m^2. Grouting mix was injected through small metal pipes inserted into the holes.

For draining of the groundwater that may have been impended after the grouting behind the wall drain pipes 16 mm in diameter were drilled to retain unchanged conditions.

Activation of the horizontal reactions and thus reduction of the load on the cantering produced several positive effects. Natural state has been established between the arch and the waterfront structure. It enabled an early removal of heavy steel cantering (Fig. 7).

5 CONSTRUCTION OF THE NEW OLD BRIDGE

Old Bridge replica has been constructed by erecting heavy steel cantering, construction of the new stone arch, lower cornice, spandrel walls, upper cornice, cobblestone surface and finally the stone parapets on each side of the bridge.

Heavy steel cantering on concrete piles was better suited than the light arch cantering usually implemented in contemporary construction because of all the original small imperfections that needed to be replicated in the new structure. After the removal of the cantering the displacements were less than 1 mm.

The design of the Old Bridge of Mostar has revealed to be one of the most complex, delicate and undertaking enterprise of the history of the interventions held over the world cultural heritage. Based on wide preliminary studies and on all the available documents of the Old Bridge, it has been developed on different sides in order to give answer to issues concerning the restoration, the preservation and the declared reintegration, respecting the structural requirements and safety security factors as foreseen by the European standards.

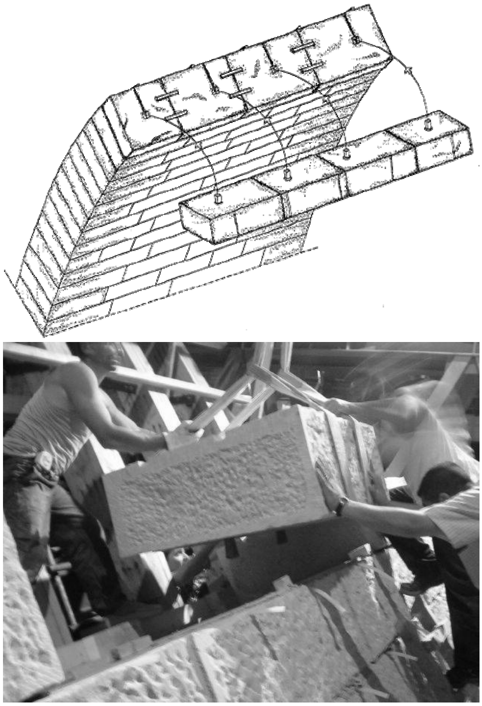

Figure 8: Placement of the stone blocks

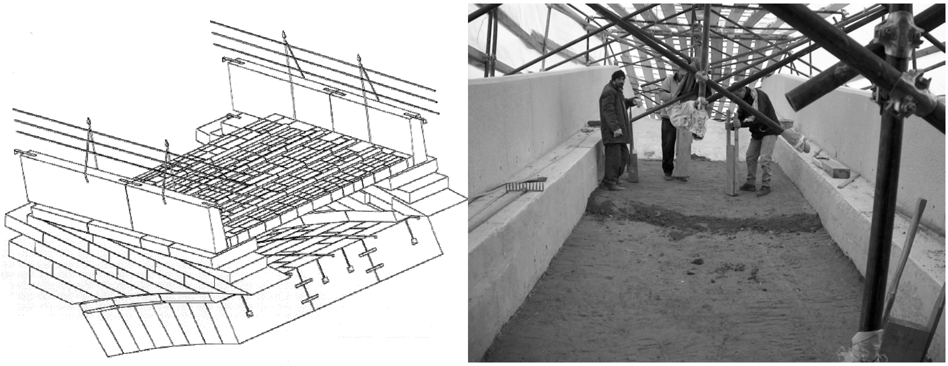

Figure 9: Cross section arch, spandrel walls and the cobblestone surface

The technical design, structured following an approach by each stone element, has produced detailed construction drawings and, with the use of computer systems, has given 45.000 levels and dimensions aimed at the managing of more than 1000 stone blocks and almost 1700 anchorage elements, evaluating all the working methodologies and tolerances (Fig. 8 & 9).

The study held over the monument, and over the recovered portions, during the performing of the task, has revealed a refined constructive technique of the Bridge according to the typological system of the metal reinforced stone, (already known in architecture, but impressively executed in this case). The design, performed in a period of almost one year time, will allow keeping the structure unchanged for what concern the construction materials, the construction techniques and the exact geometry, even if characterised by ordinary irregularities.

6 CONCLUSIONS

The bridge was reconstructed in such a way that its bearing structure is of a sufficient bearing capacity, stability and durability, and that the bridge as a whole can conveniently be used as a pedestrian bridge. The declaration between original bridge elements and new intervention bears only light and refined marks.

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