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THE MEDIEVAL BRIDGE OVER THE RIGNALLA BROOK NEAR FLORENCE: ANALYSIS AND REHABILITATION PROJECT

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ABSTRACT: Hidden in the green countryside near Florence in Bagno a Ripoli (FI), the small stone arch bridge over the Rignalla brook, left tributary of the river Arno, has been recently discovered. The Reclamation Consortium of Central Tuscany, the authority for the protection and maintenance of soil and waterways, has entrusted us with a research project aimed at a cognitive analysis of the bridge and a rehabilitation and functional recovery project for a pedestrian public use. The date of the laying of the foundation-stone in unknown: it is believed to be a "Roman bridge". The historical research, also supported by the static analysis to evaluate the degree of stability of such a structure, suggests the possibility to attribute the design of the bridge to Leonardo da Vinci.

Keywords: Stone arch bridge, Masonry, Non-linear analysis.

INTRODUCTION

The ancient bridge over the Rignalla brook was discovered in the 1970s by the "Committee for the Researches into the Material Culture of Tuscany" (Silvano Guerrini, Giovanni Caselli), who, immediately, highlighted its state of risk. In the report entitled "Summarizing Paper about the archaeological interesting places in the municipal territory of Bagno a Ripoli", sent to the Municipality and to the offices of Superintendents, you can read "*Bridge over the Romaiolo brook (Rignalla brook): in serious risk of collapse. It is the most ancient bridge in the territory of Bagno a Ripoli. From the bridge a paved road goes up to Rignalla. It must all be preserved as it represents the last remains of the pathway which led to the Parish of Villamagna*" [1].

Again in 1997, in an article by Vittorio Mechi published in the local newspaper "Macchè", this state of neglect and carelessness of the bridge as well as the necessity to restore it, is again underlined: *"...In the neighbourhood there is also a very small arch bridge, along the ancient medieval pathway, near Rignalla, which the archaeological team of Bagno a Ripoli has gibbed and anchored by means of iron tubular supports so as to preserve it for our descendants".*

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Given the state of risk of the bridge, the carelessness and the absence of maintenance, the authors, by this work, want to propose themselves as the promoters of an intervention of rescue aimed at the structural strengthening and restoration of this forgotten infrastructure, with the purpose to give it back its historical respect as well as a certain usefulness.

THE PRESENT STATE OF THE HISTORICAL CONSTRUCTION

Geometrical and architectonical description.

The historical construction, here analyzed, is composed of the bridge and a curvilinear retaining wall which starts from the bridge towards the north.

Fig. 1 - Pictures of the bridge and of the retaining wall explaining the reason of the name "Romaiolo".

Most probably the round shape of this wall is the reason for the name "Romaiolo", that is "ladle", which was given both to the bridge and the brook in the past (fig. 1).

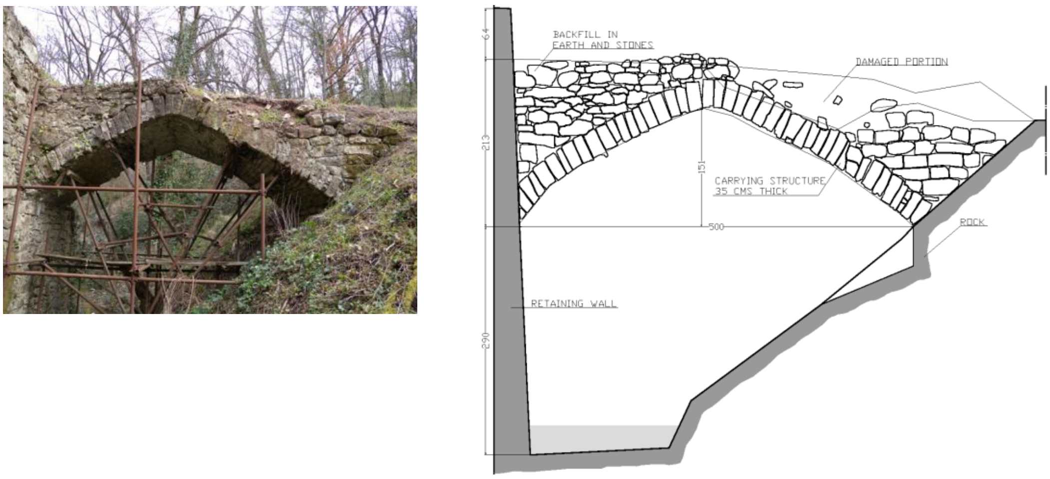

Fig. 2 - A picture of the side of the bridge from uphill (a); geometrical representation and materic description (b).

Both masonry apparatus are made of limestones (alberese) and sedimentary stones (macigno, gray sandstone), which are exposed. While the retaining wall is dry assembled, without the use of the mortar inside the joints among the stones, the masonry of the bridge still shows the presence of a mortar devoured by time and consumed by rain water in some zones.

The arch bridge is ogival shaped, but its intrados outline seems to be defined by means of two rectilinear lines rather than two curves. It covers a span of about 5.00 metres and its rise is 1.50 metres. The deck, which is about 2.90 metres wide, is composed of a stone carrying structure with a medium thickness of 35 centimetres, on which there is a dead load composed of a backfill made of vegetable soil and stones (fig. 2). On the hydraulic right the bridge is directly founded on a rocky superficial layer, while on the opposite side it is built on the above mentioned retaining wall.

The decaying condition.

The whole “bridge-retaining wall” looked so compromised that from the very beginning, the authors, immediately suggested the pressing need of urgent interventions.

The survey aimed at the geometrical and materic analyses highlighted problems due both to the decay of the materials and to structural displacements and settlements.

Observing the bridge from downhill, the lack of a portion of the deck, which is about 1.20 metres wide and a length of a half span, is pointed out. Such a lack could be due to the collapse (probably caused by excessive pressure of the soil) of a portion of the retaining wall, which served as its impost surface.

Observing the bridge from uphill, instead, the masonry apparatus shows the lack of some stones on the right side, while the ones which have remained in situ are disjointed. However, the thing most worrying is that the face arch is entirely detached from the deck, which lies behind, and shows a clear tendency of overturning. It is all certainly due to the weeding vegetation which, with its roots deeply penetrated into the backfill, disjointed some stones causing them to fall into the river-bed.

The stones of the deck were originally assembled using mortar (probably cocciopesto). By observing the bridge from the intrados, you can notice that the joints are almost entirely consumed and lacking mortar, so that at the present time we can affirm that the bridge is still standing above all thanks to the compressive forces and friction among the blocks. An intrados crack is also present in correspondence of the right haunch.

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We think that not only the lack of mortar in the joints, but also the shape of the bridge itself, not much arched, are the consequence of settlings and displacements due to the penetration of the rain water over time. Thus, the shape of the bridge, which originally could also have been ogival with a double-sloped paving or, using the slang, “cambered”, today is characterized by two rectilinear lines inclined to design an inverted V.

This shape change has inevitably modified the structural behaviour: it changed from the simple arch scheme (based on the principle by which only compressive forces can be transmitted) to a beam-kind one (subjected to a bending moment and, consequently, to compressive and tensile forces also), provoking a phenomenon reasonably worrying, because an ashlar structure is not able to act as a beam.

On the contrary, the retaining wall does not appear in an emergency condition: only the upper stones seem to be lacking, probably fallen because of the rain water which increased the earth’s pressure.

Finally, a weed layer, composed of mushrooms, mosses and lichens, hiding the masonry apparatus, is present everywhere. Thus, summarizing, biological assaults, weed development, dampness, variations of temperature, winds and rain water are the main causes of the decay of the materials and of the carrying structure problems.

HISTORICAL RESEARCH

The small masonry bridge provides a pedestrian crossing over the Rignalla ditch (or brook), not very far from its confluence in the Arno river, near the Rosano provincial road (B-road n. 34) which leads from Florence to Pontassieve, along the left bank of the Arno itself.

Here, the territory is deeply characterized by the presence of the Arno which runs windingly along a not so narrow valley before reaching the alluvial plain and increasing its speed towards the city following a rectilinear course due to its canalization. Its ancient winding run in the plain is witnessed by some sketches made by Leonardo da Vinci in the early sixteenth century.

It is said that the arch bridge over the Rignalla brook may be attributed to Leonardo himself, who is also famous for his studies about masonry arches and bridges. He provided the bases for the studies on the graphic statics of the rigid blocks of the eighteenth century, which is founded on the concept of the “lines of trust”.

It is peculiar to notice the likeness between the shape of the Rignalla bridge, with its lancet shape, and the sketch of the bridge by Leonardo in his Codici di Madrid.

It is sure Leonardo da Vinci was familiar with the area in which the bridge lies, as the Florence town council entrusted him to draw up the plan of this site in 1505 in order to divert the Arno from Pisa. Leonardo took advantage of this absurd task to design, instead, a wide scheme to make the river navigable in the stretch running from Florence to the sea; so he drew an accurate map of the area around Bagno a Ripoli.

At that time “the state of the roads was not well defined. Probably there were only short and separate stretches of the road, linking Candeli to Rosano, that people could cover only on foot or on horseback. They jointed to the hilly ways and so did not provide a continuous way down to the valley. At the end of the sixteenth century, the state of the roads along the side of the river” (Rosano Street) “had been completely defined (as you can see observing the Piante dei Capitani di Parte)” [2].

No information about the presence of the Rosano Street itself has been found before the XVI century: it is probable it didn’t exist in previous years, above all, if we consider the frequent overflows of the Arno which prevented access to Florence up to the 16th century.

The essential source of historical information has been the notary Luigi Torrigiani’s manuscript [3], which is preserved at the Moreniana Library in Florence.

During his long permanence in the territory around Bagno a Ripoli, Torrigiani had the occasion to know and describe it in detail. The described period is very vast: he himself lived in a very important historical period for Tuscany, beginning from the grand ducky of Pietro Leopoldo until the Unification of Italy.

In his description he referred to the Maps of Campione di Strade [4], which Grand Duke Pietro Leopoldo commissioned in 1774. In these maps, the Rignalla bridge is called *“The Riferrato Bridge”* or *“The Riserrato Bridge”* over the Rignalla brook.

In the work by Luigi Torrigiani you can also read that the Rignalla brook, which outlines the boundary between the District S. Maria a Rignalla and the District S. Andrea a Candeli, in the Street Plan [5], which the Government of Guelph Part commissioned in 1500, was called *Ditch of Romajolo*, and the bridge was called *Romajolo Bridge*.

The work by Luigi Torrigiani also reveals that the state of the roads in the past was oriented along axes far from the course of the Arno, developed on the hills, so as to avoid the risks of floods and the marshy waters down in the valley. Thus, the territory was crossed on foot or horseback, following directions different from the present-day ones. In the long run, such ways have lost their importance, some of them are no longer used and others do not exist any more.

Observing the maps made in 1774, Torrigiani describes the District Rignalla and provides useful information about the *Vicinal Road of the Serrato Bridge*, which "begins from the main road to Rosano sull'Arno, a few metres before the Rignalla brook flows into the above mentioned river, then it rises on the right of the municipal road to Villamagna, crossing the Rignalla brook by means of the bridge named Riserrato Bridge; (...) it is steep and not carriageable. This path was paved in the past, but now you can only see a few metres of the ancient pavement. Over the Rignalla brook the ancient bridge still exists..." [3].

According to the text written by the"notary", the state of the roads around the bridge was composed of three main roads leading to Villamagna, two of which were built before 1700: the *Vicinal Road of the Mill of Vallina*, the ancient *Main Road (via Maestra)*, which was "carriageable", and the *Vicinal Road of the Serrato Bridge* which was steep, and so "not carriageable" and that people could cover only on foot.

On the contrary, the third one, the *Municipal Road of Villamagna*, was a new road; in fact it was built only after 1700 by Grand duke Pietro Leopoldo. It was called *Main Road (via Maestra)*, so the previously mentioned Vicinal Road of the Mill of Vallina was renamed *Little Main Road (via Maestrina)*.

So, who wanted to get to Villamagna on foot, could cover the Vicinal Road of the Serrato Bridge, which used to be paved. They could cross the Rignalla brook by means of the Romajolo Bridge.

Thus, in the past, the Rignalla Bridge was in a crucial position for crossing the territory, along the road beginning in Pian di Ripoli, near the ford Varlungo, and leading to Candeli, where there was the Monastery of St. Andrea. This road went up to Majano and Rignalla, where there is the ancient stone bridge. Then this road, leading to Villamagna, reached the Oratory devoted to the Blessed Gherardo, an hermit who lived in the first half of the 13th century and was the object of public devotion [6]. This fact proves that, in the Middle Ages, the Road of the Serrato Bridge was a pilgrimage road: many people went to Villamagna from places as far as fifteen chilometres away to ask the Saint for help.

Unfortunately, no information about the existence of the bridge in the medieval age has been found: the first documents which describe it are the sixteenth century maps planned by Capitani di Parte Guelfa.

Without any doubt, its lancet shape with the intradoss and the extradoss which are straight more than curved, and the use of local stones, lead us to believe that he bridge is of medieval origins and exclude the hypothesis of its being built in the sixteenth century.

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ANALYSIS OF THE PRESENT CONDITIONS

Analyses of the materials.

To reach a high level of knowledge aimed at the structural analysis of the small masonry construction, in addition to the geometrical survey, we performed mechanical trials to test some stones, extracted from the bridge where they were disjointed.

The mechanical trials, performed at the Official Laboratory for Testing of Materials and Structures of the Construction and Restoration Department of the University of Florence, determined their specific weight (26000 N/m^3) and compression strength (40-50 MPa). Observing the load-displacement diagrams, computer plotted during the trials, it was also possible to determine the value of the compression elastic modulus (4600-5200 MPa).

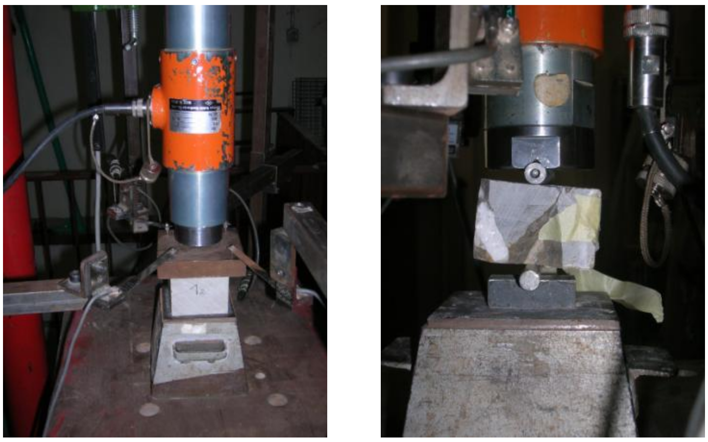

Fig. 3 **-** *Testing apparatus: compression test (a); Brazilian indirect tensile test (b).*

The trials were performed in two consecutive steps: the arrangement of the samples cutting the stones by a water saw equipped with a rotating disk to obtain regular prismatic solids; the test of the samples by placing them on the testing apparatus, consisting of a hydraulic press and four displacement transducers. The samples were tested by means of different kinds of trials: uniaxial compression (to determine the compressive strength and the elastic modulus), uniaxial compression in three alternating cycles of load-unload (to determine more accurate values of the elastic modulus), Brazilian indirect tensile tests (to determine the compressive strength deriving it from the tensile one). The regular samples with rather plane surfaces have been tested through compressive trials, as their shape was coherent with the testing apparatus. Instead, when the samples were imperfect, and thus their shape was not coherent with the press, indirect tensile trials have been performed (fig. 3).

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Structural Analyses.

The bridge structure was analysed using the code BrickWORK [7], which implements a numerical algorithm [8,9,10] for the analysis of masonry arches, vaults and arch bridges, through a discrete model composed of rigid blocks jointed without an interposition of mortar.

This numerical procedure, the result of the scientific research in Civil Engineering by the authors themselves, seemed to be perfectly coherent with the present condition of the bridge, which appears composed of stone blocks linked by means of some joints lacking in mortar.

Two structural models have been formulated. The first represents only the deck of the bridge, constrained to the soil by fixed restraints. The second considers the system "rock-arch bridge-retaining wall", to simulate the earth's pressure and also obtain the stress state in the pillars.

To evacuate the safety degree of the bridge structure and to avoid the risk of impending collapses, the structure in its present state was computed, considering the self weight of the deck of 26000 N/m^3 (value obtained from the experimental trials), and the weight of the backfill, assumed to be 20000 N/m^3, (value obtained from the technical-scientific literature), and an additional overload of 5000 N/ m^2, which represents the maximum foreseeable throng.

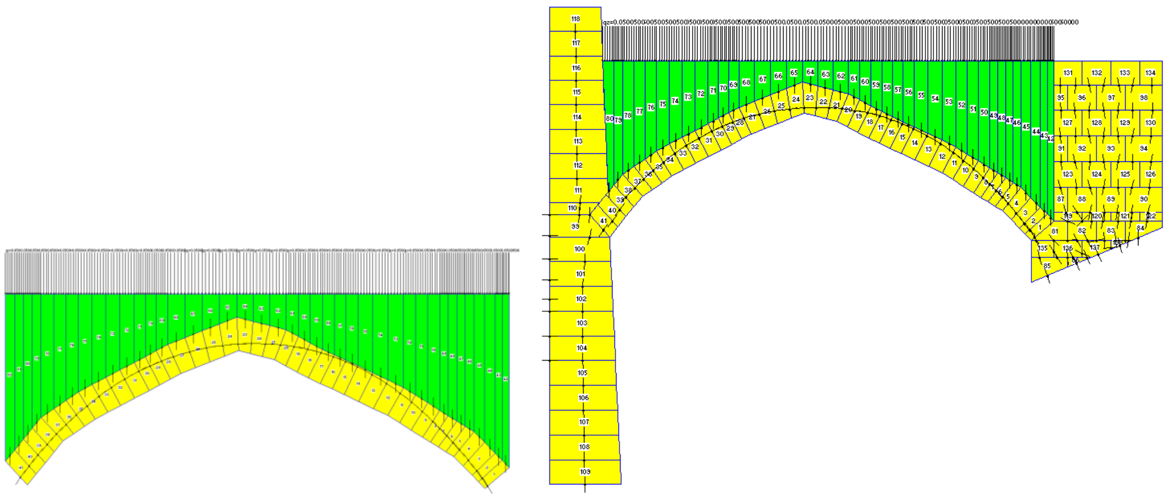

Fig. 4 - Line of thrust obtained from the structural analysis by the software BrickWORK, considering the load condition of its self weight and an additional overload: first model (a); second model (b).

The structural response, which is also graphically represented by the draw of the line of thrust, reassures and excludes the possibility of further structural damages (fig. 4).

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Moreover, considering the possibility of a future public use of the bridge, we have carried out a structural analysis under a moving load condition, in order to find the most dangerous position of the load due to people walking along the bridge as well as its peak value. Such a load has been simulated into the two models applying some increasing vertical forces to the centroids of each block, one after the other, until they reached the limit value which makes the structure unstable.
In fig. 5 the solution shown refers only to the most dangerous case; it occurs when the moving load is applied at the thirteenth block of the deck (numbering the blocks from the right spring), that is in correspondence of the right haunch, just where the presence of an intrados crack has been detected.

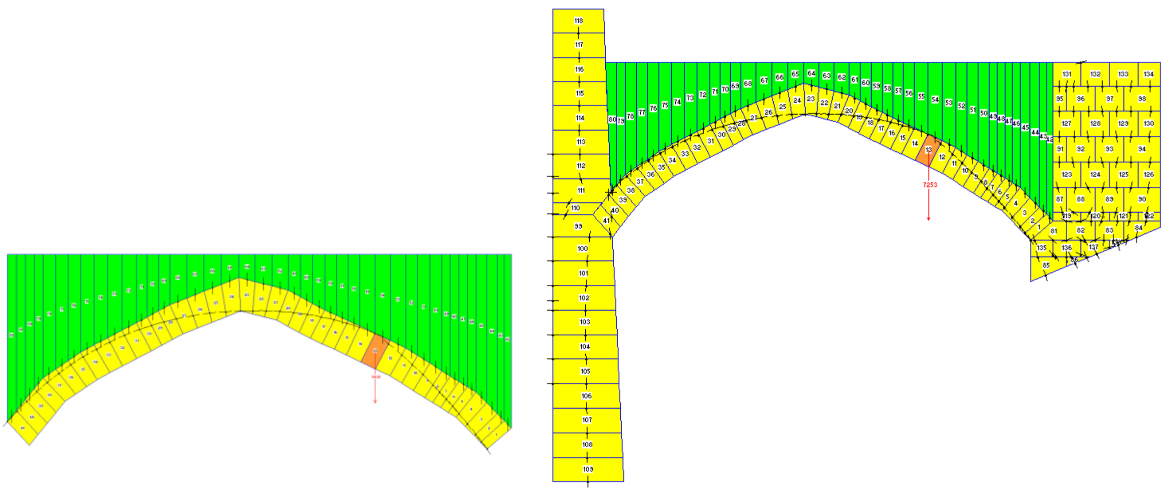

Fig. 5 - Line of thrust obtained from the structural analysis by the software BrickWORK, when the moving load is in correspondence of the right haunch: first model (a); second model (b).

Such a crack is highlighted in the numerical models by the line of thrust tangent to extrados line. The value of the peak load which makes the system unstable (64380 N) is equal to a surface pressure of 132930 N/m^2 (or, that is the same, to a distributed load of 22000 N/m) in the case of the first model; in the case of the second model such a force (72530 N) corresponds, instead, to a surface pressure of 149760 N/m^2 (or, that is the same, to a distributed load of 25010 N/m). Note that the values obtained from the analyses using two different models are commensurable values; so it assures the used methodology is good as well as the obtained results. At last, as such a peak value is much higher than the maximum additional overload foreseeable on a pedestrian bridge (5000 N/m^2), we deduce it will be possible to use the Rignalla Bridge for a public purpose.

PROPOSAL OF INTERVENTIONS

Description of the intervention.

The authors propose a strengthening intervention of the existing masonry structure and another to restore its stone exposed face as well as a project to rebuild the collapsed portions in order to return the construction back to its original shape and making it usable again.

Initial operations.

To avoid any risk of collapse both impending and during the working period, we think it is necessary to make the bridge safe as soon as possible through the building of suitable temporary wooden or steal structures: centres placed at the intrados of the bridge, gibs, restraints along the two front apparatus. Such works will completely substitute the present underpinning, built by the archaeological team of Bagno a Ripoli in the 1970s, which now appear damaged, little jointed and consequently completely useless.

Strengthening and restoration of the present masonry structure.

The structural analyses computed on the present structure, we imagined to be complete in the representation through the ashlar models, avoided any risk of collapse and highlighted a peak load thirty times higher than the additional overload, which Italian technical construction regulations foresee. This is the reason why the intervention to refill the joints with new mortar by injections is proposed, so as to link the stones both of the deck and of the two front apparatus together as well as the substitution of the present soil and stone backfill with another one capable of protecting the deck from other possible rainwater penetration. In order to choose the best material to build the new backfill, we carried out a series of numerical computations, modifying the value of the specific weight of the backfill itself each time.

From the analyses under an increasing and moving load condition, considering only its more dangerous position, that is in correspondence of the right haunch, we can see that the Rignalla Bridge belongs to that kind of vaulted structures whose behaviour improves a lot when its backfill weight increases. In particular, to obtain static performances similar to the ones in its present state (peak load of 64380 N), it is necessary to use a backfill with a specific weight at least equal to 20000 N/m^3, while using a material with a higher specific weight it is possible to obtain a higher collapse load.

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This is the reason why we propose the use of a new backfill made of water lime mortar to substitute the present soil portion, maintaining instead the existing stone portion. This solution allows the limit load to be increased and to improve the global behaviour of the structure, as the new backfill (whose specific weight has been evaluated about 22000 N/m^3) works together with the deck and it is not a simple load. Moreover, in this way, the necessary waterproofing is provided, as water penetration was the main reason for the present dislocations.

Rebuilding of the lacking portions.

To contain the material of the backfill of the bridge, the building of two new masonry longitudinal walls is proposed; they will be hidden behind the two present stone wall façades downhill and uphill, and they will be visible only where the stones of the bridge are missing (right portion of the masonry apparatus downhill).

A floor strengthened with a light FRP net will be built upon these, and it will be waterproofed by bitumen sheets. The floor will be made by means of the original stones themselves, which will be replaced in their original position.

To rebuild the deck portion downhill, which was lost due to collapse, and thus restoring the ancient original shape of the construction, the finishing of the right half part of the face arch using wooden or steal beams is proposed.

The new arch structure together with the main elements which provide support to the safety banisters, necessary to allow future public access to the bridge, will be an unique structural frame. The supports of the banisters, mostly arranged radially, will also serve as elements to anchor the boundary beam, made of wood or steal, which will also provide support to the new portion of the floor. This will be finished building a wide-plank flooring, so as to complete the original stone one.

This way of working agrees with the most recent restoration theories, which suggest technical and architectonical choices able to highlight the new parts built so as to distinguish them from the existing ones.

Indeed, to provide a spring surface to the new deck structure downhill, it is necessary to rebuild the part of the retaining wall previously collapsed. To respect the technique and the use of traditional materials, local stones will be employed, but they will be indented from the surface of the existing wall, so as to clearly state the different periods of the buildings (figs. 6,7,8).

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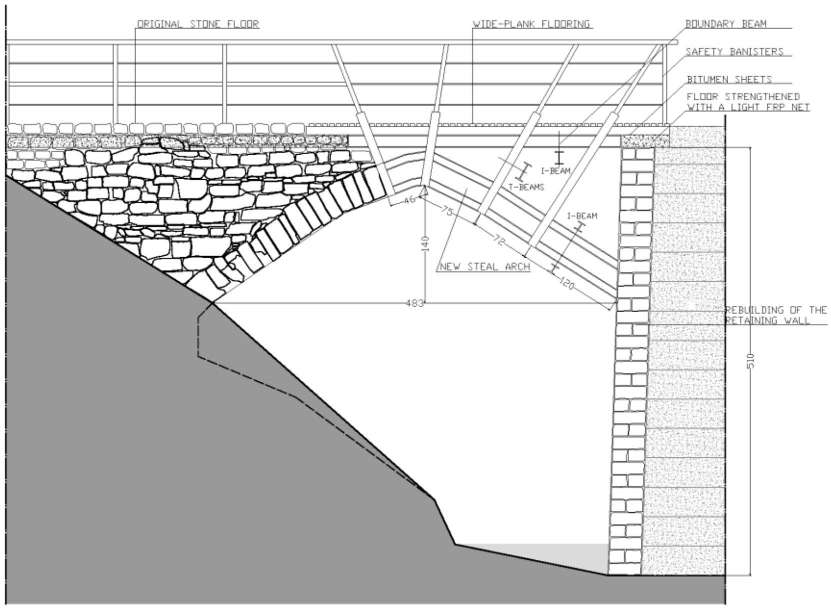

Fig. 6 - The strengthening project (downhill elevation).

Fig. 7 - The strengthening project (plan).

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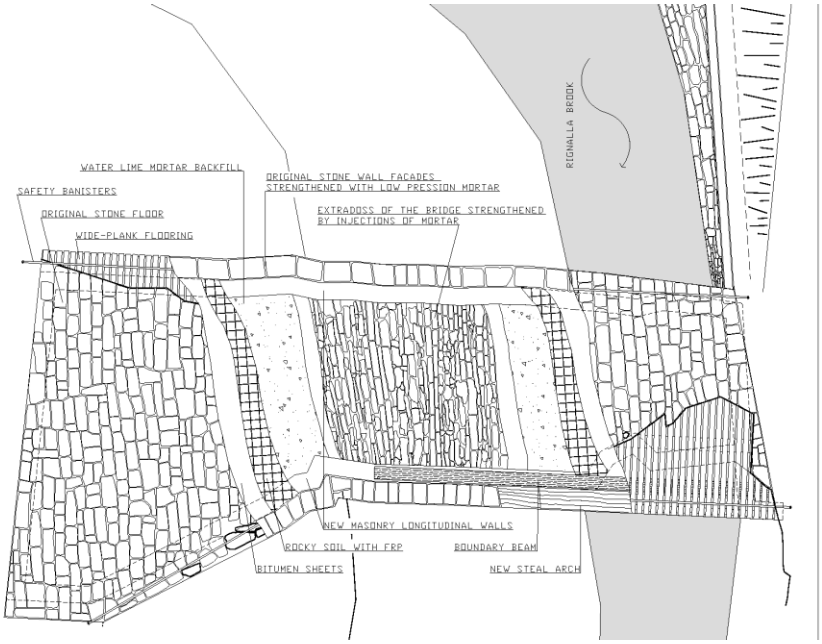

Fig. 8 - The strengthening project (layered representation).

The retaining wall intervention.

The filling of the joints with mortar in the retaining wall has not been foreseen, as it is necessary to let the rain water, penetrated in the soil, filter through the masonry apparatus to reach the river-bed; so the earth's pressure is not increased.

To avoid further stones from falling, it is then proposed to modify the slope of the soil following an angle of repose, as well as the building of a water lime mortar cyma at the top of the wall, with a back drainage; such a drainage will be created through an excavation 40-50 centimetres deep and wide to lodge an underground threaded pipe; this will allow the rainwater to be driven away from the masonry structure and lead it to the river-bed immediately.

CONCLUSIONS

In this paper the steps of the study aimed at the cognitive analysis of the small Rignalla Bridge have been described: a historical research, geometrical and materic surveys and structural analyses have been performed. At the end an intervention of strengthening and restoration aimed at future public use of the bridge has been presented.

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To avoid the bridge from collapsing, in the near future, into the oblivion and carelessness, in which the authors found it, the recovery project does not stop here. We intend to consider the bridge together with the environmental context and discover the historical road linking Candeli with the Rignalla Road and the Villamagna Road, lost in the course of ages: a trekking-way in the green countryside near Bagno a Ripoli could be a good aim to achieve.

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