# Conservation of ancient constructions and application to a masonry arch bridge

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*SUMMARY:*

*In the last years significant developments occurred with respect to the possibilities of analysis of ancient cultural heritage buildings, which result from the societal growing concern about the preservation of this heritage, together with the evident cultural and economic importance of this activity. Recommendations for interventions in architectural heritage structures recently issued by ICOMOS are briefly reviewed here, with a discussion about the proposed methodology. Then, a case study is fully detailed. In this case, the aspects of survey, numerical analysis, justification of remedial measures, detailing of the adopted strengthening and works carried out of a historical masonry arch bridge are described.*

*KEY-WORDS: Masonry, Heritage, ICOMOS, Arch Bridges*

## INTRODUCTION AND AIMS

Recently, Recommendations for the Analysis, Conservation and Structural Restoration of Architectural Heritage have been approved by ICOMOS [1]. These Recommendations are intended to be useful to all those involved in conservation and restoration problems and not exclusively to the wide community of engineers. A key message, probably subliminal, is that those involved in historic preservation must recognise the contribution of the engineer. Often engineering advice seems to be regarded as something to be sought at the end of a project when all the decisions have been made, while it is clear that better solutions might have been available with an earlier engineering contribution.

An issue related with this message is that conservation engineering requires a different approach and different skills from those employed in designing new constructions. Often historic fabric has been mutilated or destroyed by engineers who do not recognise this fact, with the approval of the authorities and other experts involved. Moreover, even when conservation skills are employed, there are frequent attempts by regulating authorities and engineers to make historic structures conform to modern design codes. This is generally unacceptable because the codes were written with quite different forms of construction in mind, because it is unnecessary and because it can be very destructive of historic fabric.

The need to recognise the distinction between modern design and conservation is also of relevance in the context of engineers' fees. The usual fee calculation based on a percentage of the cost of the work specified is clearly inimical to best conservation practice, when the ideal is to avoid any structural intervention if possible. Being able to recommend taking no action might actually involve more investigative work and hence more cost to the engineer than recommending some major intervention. Modern intervention procedures require a thorough survey of the structure and an understanding of its history. Any heritage structure is the result of the original design and construction, any deliberate changes that have been made and the ravages of time and chance. An engineer working on historical buildings must be aware that much of the effort in understanding their present state requires an attempt to understand the historical process. The engineer involved at the beginning of the process might not only have questions that can easily be answered by the archaeologist or architectural historian, but he might be also able to offer explanations for the data being uncovered.

Thus, a first aim of the present paper is to stress the role of engineering in the conservation of historical structures and the fact that an engineer, with specific knowledge in the field, must be involved from the beginning in the team of experts associated to the process. The analysis of ancient constructions poses indeed important challenges because of the complexity of their geometry, the variability of the properties of traditional materials, the different building techniques, the absence of knowledge on the existing damage from the actions which affected the constructions throughout their life, and the lack of applicable codes. In addition, restrictions in the inspection and the removal of specimens in buildings of historical value, as well as the high costs involved in inspection and diagnosis, often result in limited information about the internal constructive system or the properties of existing materials. These aspects call for qualified analysts that combine advanced knowledge in the area and engineering reasoning, as well as a careful, humble and time-consuming approach. In particular, it is noted that significant advances occurred in the last decade concerning the development of adequate tools for the numerical analyses of historical structures [2].

Therefore, a second aim of the paper is to present a real case study of a masonry structure with severe damage and major constraints on strengthening possibilities. The structure under analysis is a multi-span arch bridge, located close to Guimarães over Vizela River. Although considered to be a Roman bridge, there are no available documents to clearly corroborate this hypothesis. As the major part of the bridges, Negrelos Bridge was an important structure of Minho road network in ancient times. A detailed survey of the damage allowed concluding that remedial measures were necessary in order to restore safety. The bridge load capacity was also assessed by means of a simple computational tool based on the limit analysis theory. To assure the safety use of the bridge, by light traffic and people, repair measures were proposed in accordance with the recommendations of ICOMOS [1].

## REVIEW OF ICOMOS RECOMMENDATIONS [1]

Structures of architectural heritage, by their very nature and history (material and assembly), present a number of challenges in conservation, diagnosis, analysis, monitoring and strengthening that limit the application of modern legal codes and building standards. Recommendations are desirable and necessary to ensure rational methods of analysis and repair methods appropriate to the cultural context.

Therefore, the International Scientific Committee for the Analysis and Restoration of Structures of Architectural Heritage (ISCARSAH) has prepared recommendations [1], intended to be useful to all those involved in conservation and restoration problems. These recommendations contain Principles, where the basic concepts of conservation are presented, and Guidelines, where the rules and methodology that a designer should follow are discussed. More comprehensive information on techniques and specific knowledge can be found, e.g. [3-6]. In addition, normative and pre-normative are gradually becoming available, e.g. [7-9], at least with respect to seismic rehabilitation, which is a major concern.

## Principles

A multi-disciplinary approach is obviously required in any restoration project and the peculiarity of heritage structures, with their complex history, requires the organisation of studies and analysis in steps that are similar to those used in medicine. Anamnesis, diagnosis, therapy and controls, corresponding respectively to the condition survey, identification of the causes of damage and decay, choice of the remedial measures and control of the efficiency of the interventions. Thus, no action should be undertaken without ascertaining the likely benefit and harm to the architectural heritage.

A full understanding of the structural behaviour and material characteristics is essential for any project related to architectural heritage. Diagnosis is based on historical information and qualitative and quantitative approaches. The qualitative approach is based on direct observation of the structural damage and material decay as well as historical and archaeological research, while the quantitative approach requires material and structural tests, monitoring and structural analysis. Often the application of the same safety levels used in the design of new buildings requires excessive, if not impossible, measures. In these cases other methods, appropriately justified, may allow different approaches to safety.

Therapy should address root causes rather than symptoms. Each intervention should be in proportion to the safety objectives, keeping intervention to the minimum necessary to guarantee safety and durability and with the least damage to heritage values. The choice between “traditional” and “innovative” techniques should be determined on a case-by-case basis with preference given to those that are least invasive and most compatible with heritage values, consistent with the need for safety and durability. At times the difficulty of evaluating both the safety levels and the possible benefits of interventions may suggest “an observational method”, i.e. an incremental approach, beginning with a minimum level of intervention, with the possible adoption of subsequent supplementary or corrective measures.

The characteristics of materials used in restoration work (in particular new materials) and their compatibility with existing materials should be fully established. This must include long-term effects, so that undesirable side effects can be minimized or even avoided.

Finally, a most relevant aspect is that the value and authenticity of architectural heritage cannot be assessed by fixed criteria because of the diversity of cultural backgrounds and acceptable practices.

## Guidelines

A combination of both scientific and cultural knowledge and experience is indispensable for the study of all architectural heritage. The purpose of all studies, research and interventions is to safeguard the cultural and historical value of the building as a whole and structural engineering is the scientific support necessary to obtain this result. The evaluation of a building frequently requires a holistic approach considering the building as a whole, rather than just the assessment of individual elements.

The investigation of the structure requires an interdisciplinary approach that goes beyond simple technical considerations because historical research can discover phenomena involving structural issues while historical questions may be answered from the process of understanding the structural behaviour. Knowledge of the structure requires information on its conception, on its constructional techniques, on the processes of decay and damage, on changes that have been made and finally on its present state. The recommended methodology for completing a project is shown in Figure 1, where an iterative process is clearly required, between the tasks of data acquisition, structural behaviour, and diagnosis and safety. In particular, diagnosis and safety evaluation of the structure are two consecutive and related stages on the basis of which the effective need for and extent of treatment measures are determined. If these stages are performed incorrectly, the resulting decisions will be arbitrary: poor judgement may result in either conservative and therefore heavy-handed conservation measures or inadequate safety levels. Evaluation of the safety of the building should be based on both qualitative (as documentation, observation, etc.) and quantitative (as experimental, mathematical, etc.) methods that take into account the effect of the phenomena on structural behaviour. Any assessment of safety is seriously affected by the uncertainty attached to data (actions, resistance, deformations, etc.), laws, models, assumptions, etc. used in the research, and by the difficulty of representing real phenomena in a precise way.

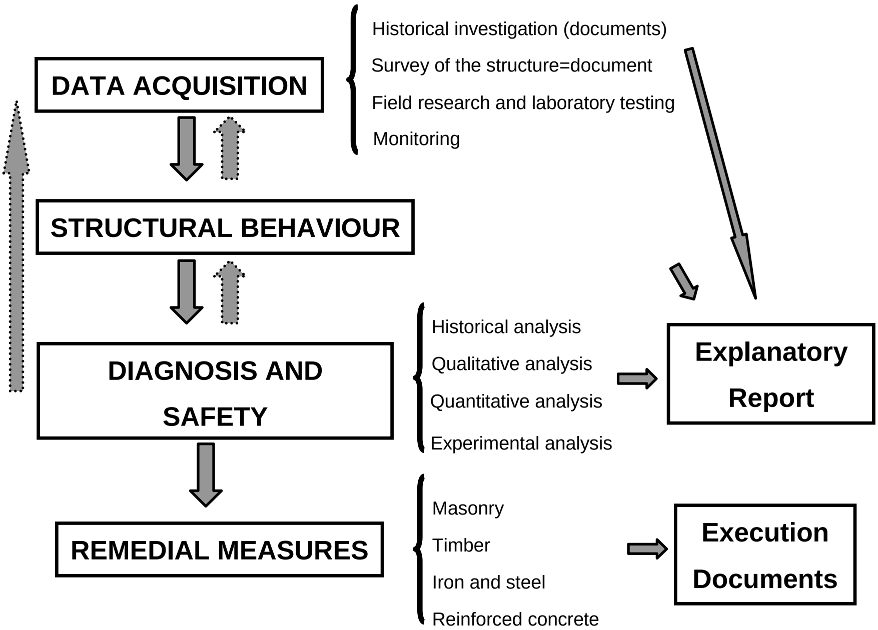


Figure 1: Flowchart with the methodology for structural interventions proposed by ICOMOS [1].

The methodology stresses the importance of an “Explanatory Report”, where all the acquired information, the diagnosis, including the safety evaluation, and any decision to intervene should be fully detailed. This is essential for future analysis of continuous processes (such as decay processes or slow soil settlements), phenomena of cyclical nature (such as variation in temperature or moisture content) and even phenomena that can suddenly occur (such as earthquakes or hurricanes), and for future evaluation and understanding of the remedial measures adopted in the present.

# ANALYSIS OF A MASONRY BRIDGE

## General description, survey and damage pattern

The Negrelos bridge, over Vizela River near Guimarães, has a flat roadway, supported by three semicircular granite stone masonry arches, with different free spans (8.0 m + 6.4 m + 8.0 m), as schematically represented in Figure 2. The bridge reaches a total length of approximately 30 m and has a roadway width of about 3.0 m. The central arch is supported by two massive piers, endowed with two triangular cutwaters at upstream and two rectangular cutwaters at downstream. Within a governmental program to clear the river from pollution, a drainage pipe was placed on the left shore, on top of an embankment made beneath arch A1 and close to the left abutment, see Figure 2 (the pipe is not visible).

Both the spandrel walls and the parapets were built with stone masonry, but successive repair works carried out over the years have changed some original characteristics as it can be noticed by the parapet wall partially rebuilt with concrete blocks.

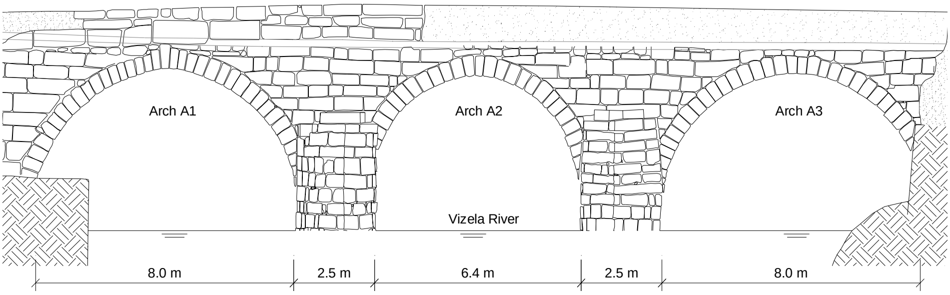
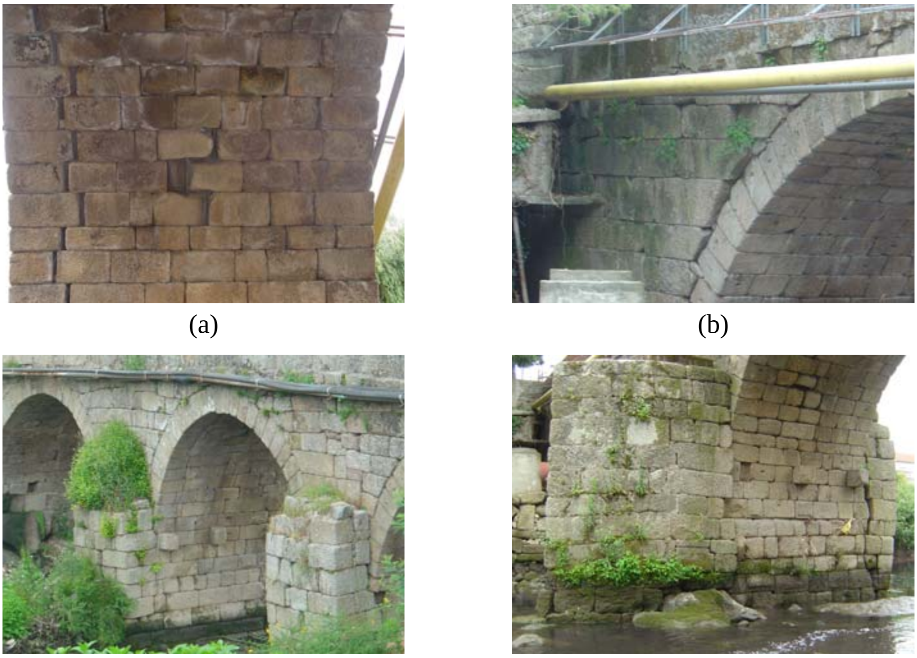


Figure 2: Negrelos Bridge (upstream view).

Fearing for the bridge safety, which was originated and further supported by its visual aspect, the local authorities requested a complete survey on the bridge, as well as the definition of a set of remedial measures in order to restore safety, if necessary. However, any repair measures to be adopted ought to take into account the architectural significance of the bridge. The survey carried out has showed that the bridge presented a pronounced damage state, where damage was mostly characterized by:

- Extensive longitudinal cracking exhibited by the central arch (A2), close to the downstream spandrel wall, clearly visible at the intrados, see Figure 3a. This was mainly caused by earth pressure in the spandrel walls;
- Lateral movements of the spandrel walls near the left abutment, which became out of plumb, most likely originated by lack of maintenance in conjunction with increasingly heavy loads, see Figure 3b;
- Generalized damage caused by vegetation, spread all over the bridge, see Figure 3c, d;

- Extensive cracking in the left downstream cutwater and minor cracking in the other three cutwaters, mainly due to existing vegetation and the lack of adequate stone imbrication, see Figure 3c, d. Also, some stone blocks were cracked. Most probably, some of the cutwaters were built or extended after the construction of the bridge.



(a) (b)

(c) (d)

Figure 3: Relevant damage: (a) longitudinal cracking in the central arch; (b) spandrel wall out of plumb; (c) vegetation and cracks in the downstream cutwaters (downstream view); (d) vegetation and cracks in the left pier (upstream view).

The deficient maintenance of the bridge along the years together with growing traffic loads seem to be the main causes of the damage pattern found during the survey that led the bridge to its actual poor condition. Naturally, the antiquity of the bridge, the water pollution and the decay of the materials also contributed to the actual degraded state.

## Carrying capacity assessment

Besides the necessary repair measures to be undertaken, also a numerical assessment in terms of carrying capacity was required in order to appraise the safety conditions of the repaired bridge to be used by light vehicles. The objective of the present numerical analysis is to have a good estimation of the maximum load that the bridge can sustain prior to failure.

Among the available computational methods proposed in literature to compute the carrying capacity of masonry arch bridges, from hand-based methods to advanced non-linear tools, the rigid block computational limit analysis method is the most generally applicable, see Livesley [10] and Gilbert and Melbourne [11] for further details.

Within the limit analysis method, the load distribution is known but the load magnitude that the bridge can carry is unknown, but it can be easily computed. Therefore, limit analysis is a very practical computational tool since it only requires a reduced number of material parameters and it can provide a good insight into the failure pattern and limit load.

Here, Negrelos Bridge was modelled as an in-plane three-span semicircular arch bridge with a 0.50 m arch thickness and a flat pavement. The necessary geometrical data was obtained from topographic surveying and visual inspection. In the absence of in-situ test results, the material properties were considered to assume typical values found in similar structures [12, 13]. In particular, a value of 8 $N/mm^2$ was adopted for the masonry compressive strength [14], whereas for the horizontal passive pressure a conservative value equal to half of the classical value given by Rankine theory was used [15]. Besides the self-weight of the materials (masonry and fill), a rolling load composed by the portuguese standard vehicle [16] was considered. This standard vehicle is composed by three axles equally spaced by 1.50 m and with a 200 kN load per axle. Using a computer program developed within the rigid block limit analysis method [17], the minimum failure load factor was found to be equal to 1.67. Figure 4 illustrates the associated four hinges failure mechanism found, where both the dead and live load pressures applied to the arch, the hinges and the thrust-line are showed.

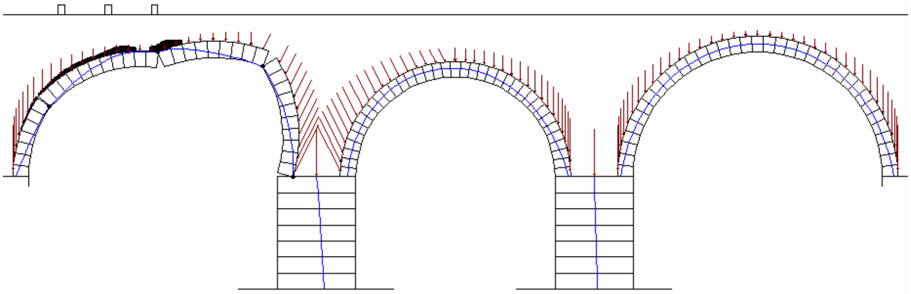


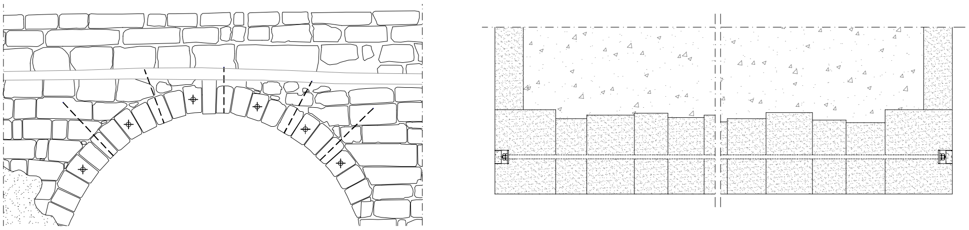
Figure 4: Minimum load failure mechanism of Negrelos Bridge.

Assuming that the vehicle crosses the bridge from left to right, the minimum failure load factor was found for the vehicle central axle positioned at 31.9 % of the left arch free span (arch A1), as illustrated in Figure 4. Since symmetrical geometry and vehicle are used, the same result is obtained considering that the vehicle crosses the bridge from right to left instead. Since the local authorities are planning to close the bridge to heavy traffic after concluding the repair works, it can be considered that the bridge will present safety conditions to be crossed by light traffic.

## Repair measures

### Description of the remedial measures

The detailed visual inspection carried out showed that a set of repair actions were necessary, namely to stop the progression of the longitudinal cracking along the central arch, to counteract the outward movement of the spandrel walls, to prevent the failure of the cutwaters and to clean all vegetation from masonry. The historical and architectural importance of Negrelos Bridge forced that any strengthening measures had to be designed in accordance with the recommendations afore-mentioned in the previous chapter. To prevent any additional increase of the longitudinal cracking in the intrados of the central arch as well as to assure its future stability, a set of four horizontal stainless steel anchors across the full bridge width, endowed with cylindrical steel anchorage plates at each side of the arch, were proposed, see Figure 5. Also, two additional shorter stainless steel anchors were used close to each springing. In addition, it was recommended a light injection of the arch, at the intrados.



(a) (b)

Figure 5: Strengthening of the central arch: (a) adopted anchor scheme; (b) full bridge width anchors.

For the connection between the arch and the spandrel walls a similar solution was developed. Five stitching anchors in each side of the arch were used with the purpose of linking the spandrel walls to the external arch voussoirs, see Figure 5a.

In order to face the out-of-plumbness of the spandrel walls above the left arch, it was decided to use two horizontal stainless steel anchors across the full bridge width provided with cross-shaped anchorage plates at the extremes. The shape of the plates was due to aesthetic reasons.

To repair the high level of damage found in the downstream cutwaters, with some stones cracked and others out of their original place and disconnected from the piers, the dismantling and subsequent rebuilding of the most deteriorated areas was proposed. On the other hand, the upstream cutwaters, less damaged but also in a poor condition, are to be injected with a lime-based grout after conclusion of the joint repointing works.

All infesting vegetation is to be removed using the most adequate procedures, and all masonry joints that show degradation are to be carefully cleaned and repointed.

In order to prevent the fines from being washed out of the fill material, leading to voids and thus affecting the carrying capacity of the bridge, it was recommended the execution of an adequate waterproofing and drainage of the pavement.

## Execution

The intervention started with the cleaning and repointing of damaged masonry joints. Special care was put on the removal of vegetation, in order to cause the least possible damage to masonry. All repointing works were done with a lime-based mortar designed to match as close as possible the stone color, see Figure 6a, b. At the same time, the preparatory works leading to the injection of the upstream cutwaters and intrados of arches were begun, see Figure 6b, c.

(a) (b) (c)

Figure 6: (a) Joint repointing of piers and arches; (b) joint repointing and injection works of an upstream cutwater; (c) injection works of the central arch.

After dismantling, the rebuilding of the downstream cutwaters was carried out using the same stones, previously numbered, or when not able to be used, with similar stones from the region, see Figure 7a. During the rebuilding, the stones in a same course were connected to each other and to the piers by means of stainless steel cramps, at every three courses. The link between two consecutive courses was achieved through the use of vertical stainless steel latches. Both the transversal full bridge width tying strengthening of spandrel walls and central arch, by means of anchors, was carried out using the same technique. In each anchor, after drilling an over-sized hole using a rotating cutting device, a stainless steel rod was placed in the hole and subsequently grouted under low pressure. In order to prevent generalized material injection it was decided to use a sleeve involving the rod. No tension was applied to the rods other than a tightening force resulting from their adjustment using a dynamometric wrench. While in the spandrel walls anchors it was decided to use cross-shaped anchorage plates, see Figure 7b, in the all eleven arch anchors the hole was made good with a slip taken from the drilled stone cores, see Figure 7c.

(a) (b) (c)

Figure 7: (a) Rebuilding of a downstream cutwater; (b) cross-shaped anchorage plate; (c) anchor plate covered by a stone slip.

## CONCLUSIONS

This paper addresses the issue of preservation of ancient structures from cultural heritage buildings. The novel ICOMOS [1] recommendations are briefly reviewed and the most relevant issues are discussed in a format of interest to other conservation specialists. The recommended methodology is presented in a simplified flow chart, stressing the importance of an “Explanatory Report”, where all the acquired information, the diagnosis, including the safety evaluation, and any decision to intervene are fully detailed. Finally, a case study on a historical arch bridge highly damaged is also presented, illustrating the possibilities of using numerical analysis in the safety evaluation of the architectural heritage. For the case study, it was possible to conclude that: (a) the observed damage level threatened the normal usage of the bridge as well as its future stability; (b) a computational numerical tool was used in the estimation of the carrying capacity of the bridge; (c) a set of remedial measures were designed and executed aiming at restoring the bridge safety.

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