Rehabilitation and Strength of Masonry Bridges

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ABSTRACT

This paper deals with the analysis and design of repair measures concerning masonry bridges. It also talks about damage in these structures and the principals to make a good diagnosis. Repair measures adopted to re-establish the safety of the bridges are described. These measures were conceived in order to respect the modern principles of structural intervention in architectural heritage.

KEYWORDS

Masonry Bridges, damage, diagnosis, maintenance, strength, management

1 Introduction

Masonry working was, throughout centuries, the great technique for bridges’ construction. Had to this, we have today a large number of examples that is necessary to conserve. Because they are part of the current road system, or represent an important architectural heritage, they deserve special attention in terms of management.

To conserve these bridges, a strategy of maintenance must be considered. It’s important regularly follows the state of art, indicating the necessity to carry through or not more specific interventions.

Neglecting this theme can result in the application of rehabilitation techniques little indicated for the structure in question. Masonry is a material with very particular characteristics which, allied to the historical value of the structure, demand specific measures. If specific measures were not taken, a wrong action can mischaracterize the structure and compromise its security.

A good operation of rehabilitation and reinforcement of masonry bridges implies, beside the use of the right techniques and materials, a correct evaluation of the damages as well as its probable cause. Equally essential is the domain of inspection methods and test equipment used for such projects.
2 Characterization and Historical Evolution

2.1 From Romans to the Modern Era

Like no other civilization, Rome developed the road concept as we know it today. The public road had as main objective the domain and military defense of a region. It was urgent that the Legion was the first to reach any part of the vast Roman map, in the best possible conditions in order to face rivals and defend traditions. This way, decade after decade, throughout the empire have been given a very intelligent transportation system, in many cases overlapped with the one we use today. Essentially with military functions, the Roman road was characterized by straight paths, always with an emphasis on the shortest path between cities. The main goal was to unite administratively important cities. The determination to shorten distances usually overlapped economic interests to include small towns in the path of major roads. Because of this strategic dimension, the route avoided crossing valleys, for the reason that they have always been associated with "see without being seen" concept and were often places for troops ambushes. Instead, Romans preferred the crest of the mountains, accepting the steepest climbs and descents in exchange for security, visibility, economy and ground strength. When it was not possible to reconcile the path, recognized as the fastest, with the surroundings, they used the greatest works of engineering: bridges.

Middle Ages is marked by a less centralized power and by constant warfare between regions. In this climate, little attention was paid to the nation’s road structure, and some of the Roman bridges were destroyed to hold back invaders. As a consequence of the weakness of royal power the strong organization of religious communities took over the construction of many bridges. Because of that, we notice the presence of chapels in most of the bridges of this period. The roads served increasingly more the population instead of a conquering army. The characteristic straight Roman path fades to give way to a more complex network that connects the various metropolis. The new bridges are part of an agrarian economy, often linked to water mills, or fit into the defensive system of towns, providing a toll tax on entry and goods transit.

In the sixteenth century, experiential learning gave rise to a more theoretical thought, requiring mathematics and geometry knowledge. Design and project involved more prudence and they systematically used sketches to represent their designs. As great technicians started to emerge, they began to be commissioned by the Royal House of major projects. In addition, in some remote areas, small local workers continued to act in a regionalized circle, what explain the technical asymmetries, aesthetic and logical of construction found at this era. The aqueducts are the great legacy of this time in terms of construction techniques, built of masonry and lime.
2.2 General characteristics of masonry bridges

The term masonry refers to a set of materials (stone, brick and ground), disposed in order to form a massive. Those materials can be set together through mortar or be simply overlapped. It is difficult to talk about the behavior of “masonry” as a sole material. According to the nature of the stones, their size, how they are equipped, the thickness and composition of the joints, etc., the material has very specific characteristics, and his behavior is the result of the mixture of all constituent materials.

The natural stone was chosen for the construction of the first bridges. It has an indisputable durability, which can be witnessed with so many ancient bridges still in service to the present day. In addition to the stone, masonry is composed of mortar. The mortar, usually lime or sand, can both serve as stucco or for laying the stones, filling the gaps and creating a uniform basis.

The transversal section can be distinguished in two different areas from a structural point of view:

- Face: larger stones, roughly regular, laid with mortar;
- Inside: smaller stones of irregular size, involved in mortar, with many empty spaces.

The technique used to build these bridges takes advantage of the characteristics of the material, focusing on arched structures, placing stone blocks subject to compression.

The Romans built the core of its bridges with pozzolan, clay baked by the heat of the volcano, which was added to sand, water and lime, to form a mortar that did not disintegrate when exposed to water. The result was a structure in which the stone is mixed with cement to form a material of great strength and also coated by paired stone. Roman bridges design presents great uniformity. Arcs are semicircular and have equal dimensions; the board rectum to allow their easy crossing and the pillars are generally rectangular.

Medieval bridges are based on more sober and moderate methods in comparison with the Roman. In fact, bridges were borders that took defense functions. They are based on less foundations in the river, and that’s why they often have larger central arches and arches progressively smaller toward the margins. The largest proportions of the central arch often dictated that the board was not horizontal, as in the Roman bridges, showing side slopes. Although the presence of hydraulic lime in medieval bridges, lack of pozzolan cement, characteristic of Roman bridges, makes the stone the principal structural element of these bridges. The arches are broken or ogival, in contrast to the round Roman’s arches. On the other hand, because of the lesser internal structure cohesion, it becomes less resistant to forces caused by the flows. That’s the reason why most have buttresses which were not common in their Roman ancestors.
More for a constructive approach rather than a return to roots-led revival, the bridges built in modern times are similar to those built by Romans. The use of a new mortar, based on hydraulic lime, allowed reusing a system of round arches. The result was more durable and flexible bridges, allowing larger arches and more slender pillars. The aesthetic concerns motivate the construction of bridges with equal arcs, such as Roman, and quickly realize that the straight path is the best way to cross them.

3 Nature and Causes of Defects

3.1 Demonstrations

- **Geometric Anomalies**, such as deformations and loss of verticality that often result from rupture of components and have a direct impact on the bridge structure operation.
- **Anomalies in materials**, ie, the stones, the mortar and other materials. This group of anomalies tends to evolve to geometric anomalies.
- **Anomalies linked to external agents**, which may be incorporated in materials’ anomalies or result in geometric anomalies. However, these kinds of anomalies are related to the environment, especially with the constant exposure to aggressive agents and lack of bridge maintenance. Examples of such anomalies are the water movement across the structure and disposal of vegetation.

3.2 Reasons

Knowledge of the reasons underlying the defects in the masonry bridges is of utmost importance to make a good rehabilitation; otherwise it is a matter of time before the bridge shows again the same signs of degradation.

The causes that may be the source of many defects in masonry bridges can be divided in five categories:

**Materials**: Despite its high resistance as material, not all rocks are suitable for all situations, particularly for building bridges, because of the existence of veins, cavities or intrinsic characteristics. Furthermore, on-site work should be followed some rules of good art, in order to increase the durability of the structure. Bad choices in terms of special design, such as the orientation of the stones, joint width, etc., do not allow making the best use of materials.

**Foundations**: sometimes, serious decompressions are observed in these structures associated with the characteristics of the terrain in which they are built. This may be because the bridge is based on terrain features with weak support, consisting of alluvium, for example. Another possibility is a heterogeneous soil, with an area with a low resistance. Decompression
due to surrounding excavations may still occur, as well as from the expansion and shrinkage of clay soils in the presence of water.

**Water:** The durability of the masonry is severely affected when it is in contact with water for long periods of time. This can occur in various forms in masonry bridges either by the rain, rise in groundwater by capillary action or sideways, through the waters that flow fields. When very wet, masonry may experience problems such as frosting or their own pollution, and the sulfate dissolved in water or salts rains aggravate the deterioration of rocks and mortar. When the board is not properly sealed and/or when the drainage devices are insufficient, it is common occur leaks. The water is transported through joints and stone blocks, promoting its degradation and dragging fine particles. Of equal importance is the action of the rivers flow on the structure and its foundations.

**Human action and accidents:** Too often, this is the cause of the greater problems in the rehabilitation of a bridge. Mankind is largely responsible for the deterioration of bridges, result of careless use, ignorance or misjudgment in previous interventional procedures or pure vandalism. Moreover, there are accidental actions, such as fires, earthquakes and lightning, which, although rare, can assume serious consequences. Also included in this category are the increasing operating loads without being properly investigated the bridge conditions to meet the new demands.

**Environment exposure and wear:** The deterioration process of a bridge begins from the time of its construction. Apart from the wind, rain and vegetation growing on the structure, this degradation can be accelerated by a noxious atmosphere exposure, motivated for example by the proximity of an industrial area.

4 Evaluation and Inspection

4.1 Inspections

Regular inspection is one of the foundations of good bridge maintenance. Must be included in a maintenance plan of the structure, which provides types of inspections are due to the bridge, which tests to perform, and how often should be made. Depending on the scale and frequency which they are made, there are three levels of inspection:

**Routine Inspections:** The purpose is to call, as soon as possible, small anomalies to attention. If not quickly remedied, could result in a state in need of costly repairs. It is essentially a visual inspection. These anomalies are, for example, cracks, water seepage, falling block walls and signs of vandalism or vehicle impact. This kind of inspection should be made annually.
Major Inspections: Involve a deeper examination done by qualified personnel in all parts of the structure. This inspection should be performed with intervals between 2 and 10 years, depending on the type of structure, its age and condition, and the difficulties in its access. The examination should be based on a predetermined check list and more sophisticated equipment in comparison to routine inspection. Depending on the conclusions from this inspection, a more detailed examination may happen, involving tests and more specific investigations.

Special Inspections: These inspections are made in special circumstances, such as the passage of an excessive loading, an accidental impact, floods, discovery of a serious deficiency or the need to retrofit the structure to a new use. Inspections should be thorough, detailed and limited to critical elements of the bridge. For example, after flooding occurs, should be performed a special inspection of all potentially affected substructures.

4.2 Testing

Testing is an essential tool to develop a proper evaluation and a good job. In the table below, the main tests for masonry bridges are depicted.

<table>
<thead>
<tr>
<th>TEST DESCRIPTION</th>
<th>UTILIZATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonic Test</td>
<td>- Determination of wall thickness</td>
</tr>
<tr>
<td></td>
<td>- Location of voids</td>
</tr>
<tr>
<td></td>
<td>- Characterization of cracks and fissures</td>
</tr>
<tr>
<td>Thermography</td>
<td>- Rigorous survey of the structure of masonry</td>
</tr>
<tr>
<td></td>
<td>- Location of voids and deteriorating mortar</td>
</tr>
<tr>
<td>Topography and photogrammetry</td>
<td>- Reconstitution of a spatial image from two-dimensional images</td>
</tr>
<tr>
<td>Flat Jack</td>
<td>- Determination of stress state</td>
</tr>
<tr>
<td></td>
<td>- Evaluation of deformality characteristics</td>
</tr>
<tr>
<td>Extraction and testing of cores</td>
<td>- Evaluation of compressive strength</td>
</tr>
<tr>
<td></td>
<td>- Determination of material’s porosity and permeability</td>
</tr>
<tr>
<td>Crack opening monitoring</td>
<td>- Accurate measurement of small displacements, joints and cracks</td>
</tr>
<tr>
<td>Inclinometer</td>
<td>- Accurate measurement of structure’s horizontal movements</td>
</tr>
<tr>
<td>Static Load Test</td>
<td>- Checking the behavior of the structure in terms of use</td>
</tr>
<tr>
<td>Helix pull-out</td>
<td>- Determination in situ of the mortar’s resistance, settlement or repointing of joints</td>
</tr>
</tbody>
</table>
5 Remedial Techniques

5.1 Infrastructure

5.1.1 Foundations

Intervention at the level of foundation is given in bridges with settlements or having relevant problems of erosion or excavation.

**Underpinning** works to transfer the existing charge for a ground with better characteristics. The basic technique of underpinning is to excavate the land on which rests the foundation, putting in that place a harder material. A more sophisticated variation of the method involves underpinning the foundation with concrete and the implementation of foundation beams to connect the various mass, which may or not head stakes.

The **injection** of cementitious grout in the foundations is used to reduce the gaps inside, making them stronger. It can also be made the injection of the surrounding soil, aiming to compress itself.

When there is scour in the masonry structure, after the fill of the infraescavadas areas, the most common solution is to build concrete walls around the foundation, not letting the vortex contact with the stone.

**Mini piles** can be used as a technique for strengthening foundations subject to settlements or required to support additional load. They consist of metal pipes of small diameter, inserted into holes, and then injected with grout. Mini piles provide a direct link between the existing structure and a land with appropriate conditions to support the loads they bring.

The **strengthening with concrete beams in the basement walls** operates primarily in order to give greater strength to the foundation, preventing the legs rotation.

5.2 Superstructure

5.2.1 Pillars

**Repointing of joints** is the most common operation in the rehabilitation of masonry bridges. It consists of removing deteriorated mortar with water and placing the new mortar.

**Injection** of the pillars is made when the present structure is inconsistent, with a high distribution of voids within their vaults or cracks. It intends to restore the stress transmission of compression between the masonry components.
As reinforcement, you can also use stitching for some structural elements, forming a kind of sewing that confines the elements and increases its resistance.

Another method of strengthening widely used corresponds to a "general jacking" of the pillars. In this technique, after the plaster had been properly cleaned and chopped, a metal mesh is put around the pillar, and then projected on it concrete. Additionally, you can run up a wall of stone blocks around the pillar.

Pre-stressing can also be used to reinforce the masonry piers creating, consequently, a state of high compression, which is not a problem for masonry structures because they have a high compression resistance.

5.2.2 Arcs

Many of the techniques applied in arches are similar to those used in other structural elements. Is the case of injection, to eliminate the gaps of the joints, or the placement of stitching to limit the cracks opening and arcs removal.

Stitching is a technique to strengthen masonry arches, in order to increase its compressive strength and the cutting and joining fractured elements. It is a method of consolidation which consists in the placement of metal rods into holes that routinely cross the structure from one end to another.

When it is possible, an arc can be enhanced by low building with a relief vault, using as constructive solution masonry, steel or concrete.

If the structure is too damaged, it may be a good solution to intervene transferring the load to a new structural element, such as a new interior arch of reinforced concrete.

To relieve the weight of the structure, the old filling material can be replaced by a lighter material such as leca’s concrete.

5.2.3 Spandrel Walls

In addition to the usual repointing of joints, the traditional method of increasing the resistance of such walls to outward movement involves the use of tie-bars.

Tie-bars are used when spandrel walls assume deformation (forming a bulge outward, for example) or when cracks appear in the intrados of the arch. This technique tends to counteract the forces that lead to its rotation or horizontal displacement.
5.2.4 Board

When the bridge’s drainage system and waterproofing is insufficiently or no exist at all, it has to be made. There are a wide variety of systems and waterproofing materials. These works are usually carried out by a specialized company, and the method selected will depend on the circumstances in which the work is performed, if there is no other work to be performed, the time available, the size of the job, the season and the services present. Sometimes it is necessary to open gargoyles through the masonry or forwarding the water to drainage systems in the area.

5.2.5 Riverbed

Sometimes it is necessary to act not only in the structure but also in the riverbed. The erosion caused by the flood introduces deformations in the ground that can result in instability of the structure.

Riprap mattress is a layer of rocks, dropped or placed in hand near pillars, and is the most often solution to counteract the erosion effects due to its easy design, implementation and relative cost. The basic principle of this technique consists on placing heavy rocks in the riverbed that can resist better by shearing stresses and erosion along the pillars. These rocks are usually associated with geotextile layers, which prevent the sediment aspiration through the blocks interstices.

6 Conclusion

The most effective results will be achieved through planned maintenance – work undertaken in accordance with a soundly based system of priorities, each operation properly planned and organized in advance, with the necessary labour, plant and materials assembled ready for use when required. This calls for a systematic and disciplined approach. Properly applied, it leads to a greater margin of safety against failure and a reduce risk of having to resort to unplanned maintenance – unforeseen or emergency action to prevent imminent unserviceability or collapse.

When it comes to practicing rehabilitation and strengthening interventions, it is essential have in mind that masonry bridges are representative of a large range of ages and construction techniques. They are part of a rich heritage that should be mischaracterize as little as possible. The techniques of reinforcement may be more or less intrusive, and its implementation must be properly studied for each particular case.

References

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