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THE ADAPTATION OF MASONRY ARCH BRIDGES. THE CEREZO BRIDGE EXPERIENCE

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Abstract: *The construction of stone bridges, as is well known, has been beeing developped along the XX century. That construction has provoked that enclosed in this moment of XXI century is very important the percent of masonry bridges that are still in use. The decisition about the criteria of how to rebuilt those bridges has very different origins, and, how we will see later, not always are technical criteria. In this article we are going to make some review about the variables that appear in the process of repairing or strengthening of structures of masonry arch typologie. Between them, we can say: initial situation, future use, the magnitude of the bridge, the hystorical importance, the importance of the road where the bridge is built, the proximity to a village or city, other posibilites to cross de river, etc. We also will make some considerations about not technical criteria that can became very strong and very important in the decisition of how to make the repair. Afterwards this introduction we will present the repair and extension of Cerezo bridge on the Tiron river (Burgos, Spain). It´s presented the initial problem and it´s explained the criteria adopted. The Cerezo Bridge is a bridge of five spans fifteen meter length each one, that means 75 meters total length. Its typologie is of stone low rised arch, and is dated in XIX century. The initial width was five meters and some of its vaults were in critical situation, near from the collapse. In this article is explained also all the work of the extension to nine meters wide, and the strengthening of the vaults traying always to considerate the variables of funcionality, aesthetic, period and cost.*

1 INTRODUCTION

The construction of stone bridges, as is well known, has been developed well into the twentieth century. A fact that has meant, even at this stage of the 21st century, that a considerable percentage of masonry bridges are still operational. A review of the different expansion techniques for masonry bridges will be carried out in this paper, as well as a review of the problems generated by construction works on the bridges – not always in economic or technical terms – and its application to a specific case, which is the expansion of the Cerezo de Rio Tiron bridge in Burgos (Spain).

2 ALTERNATIVES TO THE EXPANSION OF MASONRY BRIDGES

Three different situations may be identified when working on a masonry bridge: expansion of the bridge, restoration of the bridge, and bridge reinforcement

We shall refer to the restoration of a masonry bridge when attempts are made to recover its initial appearance following the general principles established for restoration techniques. Among the existing criteria, reference may be made to those for which a broad consensus exists, such as not altering the form or the materials, rebuilding using similar materials and techniques and, wherever possible, not attempting to imitate the old materials by using new materials.

We shall refer to the structural reinforcement of a bridge when an attempt is made to give it greater structural resistance than it was initially designed to have, generally as a consequence of a new use having being assigned to it. Reinforcement works may be carried out by conserving the attributes and old materials, or by using totally new materials placed over the original ones.

Finally, we shall refer to the expansion of a masonry bridge when we increase its surface transportation capacity as a consequence of an increase in its cross section. At the time of carrying out an expansion work, it is common to find different shortcomings in the same bridge and therefore restoration work is carried out on its form and its materials that have deteriorated over time. Finally, in an expansion work, it is not uncommon for the bridge to be subjected to a load greater than that for which it was initially designed to have and it might, therefore, be necessary to carry out structural reinforcement works of a general nature at the same time.

Centring our attention now on the principal question of masonry bridge expansion works, the problems to be solved may be summed up as follows: an increase in the platform, a mechanism through which the load is transmitted to the foundation, and a review and/or a reinforcement of the foundation

2.1 Increasing the platform as a solution

Overhanging platforms over the old tympanum: There are different ways:

- Internal structure that transfers the load from pillar to pillar and which overhangs the tympanum. This solution usually involves an amount of excavation of the inside of the extrados of the vaulted arch in order to be able to house the new structure. It can be done depending on the amount of the existing filling above the keystone of the arch and for moderate spans where the edge of the new structure does not need to be too big. The supporting structure can be of various types: continuous stone slabs or, otherwise, the longitudinal ribs, beams and transversal proyecting overhangings.

- Flagstones resting over the filling of the vaulted arch and lateral tympanum, which overhang the tympanum. This is the most economical solution, though the vaults are not always prepared for this increase in the load. The primary resistance mechanism is the flagstone that receives the usage overloads and transfers them to the filling. This, in turn, transfers them to the masonry vault. It is necessary to carefully recalculate the vaults and their capacity to adapt to the variation of the pressure lines, and also to study the resistance of the pillar foundation. This is the work that demands least intervention with regard to the original bridge and can be suitable for those vaults which have been designed with some leeway, for small overhangs or for small loads. It is advisable not to load the tympanum vertically and that the flagstone rest in contact exclusively with the filling of the extrados. It is also very necessary, with the increase of the thrusts due to the new overloads, to verify the lateral stability of the tympanum. If they cannot withstand the new thrusts, they can be braced horizontally between them using threaded rod mechanisms.
- A structure that is independent from the original bridge. In this case, the idea is to build an internal bridge that is capable, by itself, of withstanding the new loads. The new structure withstands the loads and it channels them to the new foundation, and it can even become the support for the elements of the old bridge. The latter remains as a skin of the new structure, supporting only its own weight and providing an external appearance similar to its original facade.

Displacement of the old tympanum. This is another possibility used extensively to expand the platforms. Amongst its advantages is the fact that the bridge elevations are not modified, and, to a user looking at it from a distance, its facade appears similar to the original appearance. The tympanum displacement makes it necessary to strip down the masonry work stone by stone, by using a numbering process, and later on to have them repositioned at the new location. A negative aspect of this solution is that the flow of water under the bridge is somehow modified, as the channelling effect is greater compared to the first solution. Another important aspect, which has strong economical implications, is to consider whether the expansion is symmetric or asymmetric. The decision depends generally on the bridge's environment, and frequently means the expansion has to be symmetric, which therefore means that both tympanum have to be dismantled. The solution of expanding the arched vaults by expanding the tympanum can give rise to several choices:

- Expanded Masonry Vaults. The same age-old construction technique is followed. Today this solution involves a high labour cost. It has, however, been used on occasions right up until the last century.
- Expanded concrete vaults. This solution has been used very frequently during the last century and it remains a valid solution in our times. The only way of deciding on the implementation of arched vaults with different materials is to walk along the underpath of the bridge. In order for the work to look right, it is necessary to dismantle, apart from the tympanum, the last ring of the vault and to put it in again as the framework for the

concrete extension. On occasion, some extensions have been carried out without taking this last precaution, trying to imitate the joints between stones but the result has not been very appropriate.

2.2 Mechanisms for the transfer of the load to the foundation

Use the vault mechanism by two ways:

- Supporting the masonry vault whether expanded or not: this would be the appropriate way forward for a platform extension with tympanum displacement or for an extension with stones resting on the filling. It is necessary to recalculate the resistance capacity of the vault.
- Building a new internal vault: this solution makes it necessary to clear out the extrados of the old vault in order to house the new structure, and to build an additional structure for the transmission of the loads of the stone work to the new vault. This solution can be the use of longitudinal tympanum-arch beams or the use of transversal vertical diaphragms to support the new vault.

Utilize flexing mechanisms with beams or flagstones. The flexing mechanism makes it necessary to use high edges in relation to the spans and this starts to become an important cost, which usually makes it necessary to increase the slope of the highway which is not always possible. An alternative is to use tympanum-arch beams without them resting on the vault. This frequently involves having to eliminate part of the plaster filling.

2.3 A survey of the overhaul or reinforcement of the foundation

A bridge expansion always means the increase of the loads that reach the foundation. The new expansion has to be based on legal instructions related to works on highway bridges, and these are usually very strict. What is more, it is usually difficult to obtain data on the characteristics of the existing foundation. It is also very rare that construction plans can be made available for the latter. At this point, the study of the geological profile of the terrain and the study of possible observed deficiencies are two important aspects in order to be able to ascertain data on the existing foundation. This issue is, however, of vital importance for the extension work. One possibility is to carry out improvement techniques on the supporting terrain, injecting mortar either from the slope itself or else from the riverbed if it is accessible. Another solution is to carry out an extension of the foundation, from the slope itself, using micropile techniques. In this case, it is important to study with great care the connection between the transfer mechanism of the overloads being studied and the foundation itself.

3 VARIABLES THAT INTERVENE IN THE DECISION MAKING PROCESS

The Several choices have been mentioned in the previous section, which are strictly technical when it comes to deciding on the interference criteria on the masonry structures. Nevertheless, as we shall see later on, other non-technical issues exercise great influence on the criteria for carrying out work on the masonry bridges that are highly established in their environment. Usually, the need for the work, is frequently due to the appearance of new demands as a consequence of new usages. As an example we can quote the case of having to add two or four lanes for vehicles and wide pavements for pedestrian use, as well as conveying urban services that until this time had to a greater or lesser degree been attached to the exterior façade of the old bridge. The first question to be pondered after having decided that a new bridge is necessary is whether: to build a new bridge at a nearby location, to build a new bridge at the same location, or to expand/reinforce the existing bridge

We shall now outline a classification of the variables that influence the adoption of one or another of the solutions:

- Social Issues - Nowadays, this is an issue that frequently influences every aspect of the work. All masonry bridges, be they “recent” from the last century or otherwise have survived a few generations and are therefore preserved in the collective memory of our society as being there “all of our lives”. In addition, they are made of a natural material such as stone, which can be considered in society as a 'majestic' material. All of this implies that the criterion for one bridge's substitution with a new one has to be well-grounded, otherwise it will face the opposition of all social groupings in the area where it is located. The decisions most frequently adopted are the building of a new bridge, leaving the old one for pedestrian use or the expansion and reinforcement of the actual bridge.
- Political issues - Work improvement decisions under the actual administrative structures correspond more often than not to political criteria, which are influenced directly by the social pressure that has already been commented on.
- Economic issues - Economic issues have more influence during the building work phase, but less influence in the decision making phase regarding whether a new bridge has to be built or the existing one reinforced.
- Technical issues - Technical developments over the last few years have been so great that it is now possible to carry out almost any improvement work. The only difference relates to the cost. In any case, once the parameters of the problem are set for each case, there are always one or more possible solutions that are more appropriate than others, or some work that is less advisable.
- Historical-aesthetic issues. They are of vital importance when taking a decision. Even among the different masonry bridges some differ from others, be it because of the state in which they have been handed down over the generations, the quality of their stonework, its cutwaters, their dimensions, etc. The more important they are from a historic-artistic point of view, the stronger the criteria for their conservation will be and the greater the justification to make higher investments.
- Actual state - The better the state a bridge is in, the easier it will be to justify its conservation. On occasions, the degree of deterioration is so great that it becomes almost impossible to take up the cost of its restoration and reinforcement.
- Dimensions - We have commented before on the fact that the dimensions of the bridge determine some of the possible solutions. Regarding this aspect, we would have to consider other variables such as the filling over the keystones of the vaulted arches.

- The importance of the highway network where the bridge is located - The more important the highway over which the bridge is, the bigger the capacity of the public administration in charge of the works and the greater the capacity to study alternative solutions.
- Proximity or otherwise to a population nucleus - The closer the bridge is to a nucleus of population, the higher the influence of the social environment in decision making regarding the criteria for the intervention. On other occasions, the work is motivated by a change in the layout and then the fate that awaits the masonry bridge is uncertain: anything from reaching an honourable retirement, restoration and relegation to nothing but pedestrian traffic, to being condemned and abandoned without even a minimum investment being made in it.
- Crossing alternatives - At times, crossing over the old bridge is the only means of communication between the nucleus or urban area, which is the reason why work on the bridge will leave part of the population cut off during a long period. Under these circumstances, criteria for alternative bridges or techniques that will shorten the execution time of the work will have priority over economic criteria.

Bearing in mind what has gone before, three phases can be identified for the intervention process which all involve decisions regarding: the criteria for substitution or expansion, the criteria for expansion: insofar as it effects the exterior appearance and the technique to employ for the expansion. The following graph displays the relative influence of each sector in the decision making process for each phase:

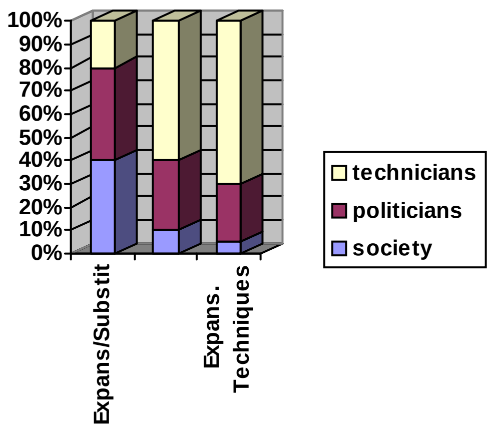

Figure 1 : Decision criterion

4 THE CEREZO DE RIO TIRON BRIDGE

4.1 The need of expansion

The Cerezo de Rio Tirón bridge, which is located over the river of the same name, is made of five low open arches, presumably from the XIX century or the beginning of the XX century. The span between the pillar axes is 15 metres, which adds up to a total length of 75 metres. The width of the vaulted arches is 0,7 metres. The net space to be crossed by the vaulted arches is 13 metres and the rise to the circumference of the arch is 15 metres. The ratio between rise/span is 1/5, the ratio between the thickness of the vault (t) and the span (l) is about 1/19. The initial width was 5 metres including the stone parapets. This width has been carrying two traffic lanes, plus pedestrian traffic, plus service crossings. And also, due to the strong industrial growth in the area, the percentage of heavy traffic was very high. The expansion requirements were: the extension of the road surface to 6 metres for two more lanes of automotive traffic and two lateral pavements of 1.5 metres for pedestrian use. At the same time, some cracks could be seen in some of the bridge's vaults, a strong erosion of some of the stones and filtrations around some of the foundations that were worrying.

4.2 Problems relating to its expansion

As regards its geographical configuration, this is an urban bridge which, even though located in one of the city exits, still serves to inter-connect urban neighbourhoods. Closure to traffic implies a detour of several kilometres in order to get from one place to another. What is more, it was the most frequently used city exit road and, therefore, its connection to the rest of the closest urban nuclei entailed a big detour. The possibility of leaving the bridge for pedestrian use and building a new one nearby was also impossible.

Figure2 : Initial state

4.3 The decision taken

In view of all the determining factors, the decision was taken to look for a solution that would comply with the following factors:

- respect for the characteristics of the bridge, altering its external configuration as little as possible
- reduce the period traffic is held up to an indispensable minimum
- build a provisional foot-bridge for the pedestrian traffic
- complete everything within the previously established budget limitations

In order to accomplish this, it was decided to build an internal structure in the form of a reinforced concrete vault that would use the masonry vault and its tympanum as lost form works. In order to do this, the emptying of all the filling of the bridge would be done with the added advantage of lightening to some extent the loads on the old foundation. The new structure would, however, rest on new concrete micropiles that would rest on resistant stratum at approximately 10 metres in depth. The expansion would be obtained with projecting wings, which, together with the core and concrete vaults would configure a box section and a beam of variable edge size resting on an foundation that transmits the loads directly into the new foundation. The foundation was reinforced with micropiles that were worked from the surface and cut later to make foundations at the lower level of the beginning of the new concrete vaults.

From the point of view of technical analysis, preparatory and reinforcement works were carried out. One of the preparatory works that may be highlighted is the placing of plaster markers on the vaults, the tympanum and the piles in order to evaluate structural movements before the work was carried out, during the work itself and following its completion.

With respect to the structural evaluation of the original masonry vaults, a specific software was written for the vector analysis which concluded that the existing masonry vaults, as long as they were in good shape, were capable of withstanding the tension caused by their own weight, the filling and the actual traffic loads. Nevertheless, during the construction process extremely heavy loads occurred, which came about due to the location of the excavating machinery between the axes of the pillars and the keystone of the vaults, with the filling eliminated on the opposite side and part of the filling not having been eliminated on the side of machinery. This load charge, plus the fact that some of the vaults were not in a good state, meant a false work process became necessary.

The structural analysis of the new structure was carried out using a double model. The first one was a bar analysis through a matrix analysis. The second one was an element through plaque elements of finite elements. Both models were carried out in three dimensions and represented the total length of the bridge.

4.4 The partial demolition

Here, we refer to the process by which the filling of the extrados of the vaults was emptied out, since at times this intermediate status with some openings bearing a load on one side and others not loaded on the other side can cause instability of the vaults. To do so, and due to the impossibility of carrying out the unloading simultaneously in a symmetric way for each half of each of the vaults, it was decided to carry out the emptying with the masonry vaults resting on a falsework, which was also kept in place during the construction period.

4.5 The construction

After the emptying process was completed, we continued to repair the extrados of the existing cracks in each of the vaults. A filling was made with mortar so that each of the cracks was completely filled. Simultaneously, the micropiles were put in place and it was observed that, due to the amount of mortar used, the porosity of the pillars and the terrain of the old foundation was diminished at the same time. The concrete structure was built up following the logical order of the vaults, the core and overhangs. These had a variable edge which was minimal in the end to increase the lightness.

All the services that were hanging from the old ornamental covers were put in conduits under the pavement. The old heavy stone parapet was substituted by a cast iron railing, demarcated by stone columns that were in line with the pillars and street lamps of a traditional appearance, which lent the bridge a lighter look than that of the initial design and allowed the reduction of the load at the end of the overhang. The bridge was finished with a stone support of a stone similar to the original stone of the bridge.

4.6 The new image

All the ornamental covers were finally cleaned with low-pressure sand blasting and treated with herbicide. The kerb under the bridge was also protected in order to alleviate any erosion that could be caused by flooding.

Figure 3 : Final state

Figure 4 : Final state. Transversal section

12 CONCLUSIONS

The expansion of the Cerezo de Rio Tirón bridge was carried out after a long period of study, after which it was possible to perform a rapid intervention at a reasonably moderate cost. After completion of the works, it could fairly be said that the planned objectives had been met: functional and structural expansion, increase in carrying capacity, restoration and improvement of the old structure and greater resistance to erosion. The cost was lower than that of a structure with modern attributes and which would also have had to include the demolition costs of the old structure. The actual completion time has been a lot shorter than that of any other alternative and even shorter than the time estimated in the actual implementation plan. A 12-month completion time was foreseen, which was reduced to an actual time of 9 months during which traffic was interrupted for only 5 months. In that period, it would have been impossible to build a new structure that included the foundations.

The rehabilitation of old bridges[i,ii] is a viable option to be considered in situations, such as the one outlined in this case study, even though it may not always be possible to meet the demanding challenge of carrying out a long lasting intervention within an acceptable time frame, at a reasonable cost while respecting sensitivities related to the built environment[iii].

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