Brick arch bridges in the High Cauca Region of Colombia: A forgotten construction tradition

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ABSTRACT: This document presents partial results of a much broader research project that has recognized historical and technical aspects pertaining to a set of 34 historic brick arch bridges, 20 of which still exist; all with diverse geometric characteristics and singular dimensions. The methodological process is exposed as was carried out with one of them and conclusions are presented, which can be extended to almost the totality of the cases studied for the purpose of offering analysis alternatives to professionals interested in the rehabilitation and conservation of the South American architectural and engineering patrimony.

1 INTRODUCTION

1.1 The location

The geographic region of High Cauca lies in to the southwest of Colombia’s current territory and has, today, close to 230 thousand inhabitants. Its principal city is Popayan, founded by the Spaniard Sebastian de Belalcazar in 1537. The city was built some 1737 meters above sea level and it is located at 02°26′39″N and 76°37′17″W. Its average yearly temperature is of 19.8°C, although there are strong fluctuations in temperature for short periods of time. Its annual precipitation regime reaches 1941 mm. The region also evidences intense seismic activity, which for centuries has been affected earthquakes of considerable magnitude; the most recent of which took place in 1983 with an intensity of 5.5 degrees on the Richter scale, causing great material damage and loss of human lives.

1.2 Brick arch bridges in the Cauca region

In spite of having a relatively hostile environment threatening the conservation of buildings, the High Cauca region was, since its colonization (in the early part of the 16th century), of high strategic value – given its being located at an intermediate point between the port of Cartagena de Indias and the commercial centers of Quito and Lima (Fig. 1). This condition gave added importance to network of roads in Popayan and to its works of infrastructure in the regional system of communication paths (Galindo, 2004) and motivated local authorities to build at least 34 brick arch bridges between 1718 and 1920.

Each of the bridges has a set of particular geometric and dimensional characteristics, following Mediterranean tradition standards related to the preparation of construction materials (brick and mortar), the fabrication of centerings, the laying of rings, the dimensioning of piers, and in general, all those elements related to the conformation of structures that have lasted for decades.

This paper will explain the historical genesis, along with the constructive and structural characteristics of one of the most significant bridges of this group: the bridge built near the city of Popayán between 1769 and 1778 over the Cauca River, as part of the roadway between this city and the city of Cali, which is located 120 km to the north.
2 GENERAL DESCRIPTION OF THE BRIDGE OVER THE CAUCA RIVER IN POPAYÁN

2.1 Geometry and dimensions

The brick arch bridge over the Cauca River in Popayán, is 153 m long and has a half-point main arch with a 19.06 m diameter, which crosses the variable current river. It also has 3 half-point leveling arches, leading to the slope on the north side; while on the southern side the main arch is directly supported upon a natural rock support vertically fitted to the ground (Fig. 2).

The structure has a constant 5.84 m width throughout its whole length. It is entirely made of solid clay brick joined with lime mortar, although beneath the main arch there are some rows of etched stone – construction material often also found on the typanums of the bridge and on the clefs of the vaults. A sole cutwater with a diamond-shaped base is found under the extreme north section of the main arch and it is also entirely built with brick. The dimensions and dimensional ratios are given in Table 1.

2.2 History of the construction of the bridge

The genesis of the structure of the bridge over the Cauca River is kept in several dispersed documents, which allow its partial reconstruction. In the Historical Archives at Universidad del Cauca (Popayán) there is a document dated in 1753, which registers that priest Simon Schenherr, member of the Company of Jesus and master builder in charge of the construction of various religious buildings in the city and participating member in the design phase of the bridge construction. He authored two blueprints each corresponding to the same bridge.

The first of the blueprints (Fig. 3) bears a drawn of a covered wooden bridge, raised over four pillars with triangular cutwaters on each face, two of them with foundations in the water. The bridge roadway surface was made up of 3 spans and reached a total approximate length of 34 m, assembled over longitudinal beams supported above the pillars through beams at 45° angles. Next to the drawing, there are also indicated the amounts of construction materials necessary for its execution.

The second blueprint (Fig. 4) reveals a 3 arched masonry bridge: the two arches of the extremes with 24 m diameters and the central arch with a 6 m diameter, supported on 4 pillars with cutwaters of equal geometry, two of them set at the river bottom. The bridge roadway surface has a double slope and according to a notation on the drawing, it was 4 m wide.

For unknown reasons, the bridge could not be built following any of Schenherr’s designs. Additionally, he did not participate in directing the work.
In another document kept in the Nation’s General Archives (Bogotá) there is testimony relating how, during a first stage of the work begun in 1769, the bridge collapsed at the precise moment of closing one of the brick arches – due to the lack of technical direction. The final construction was left to Francisco Basilio de Angulo and Josep Hidalgo de Aracena.

Once in service and for decades, the bridge over the Cauca River was always considered one of the best in the region and the nation; for example, English colonel J. P. Hamilton briefly mentions it in his book (Hamilton, 1827) as part of his journey between Popayán and Cali, just prior to the earthquake of 1827 that affected the region and destroyed several temples and caused severe damage to the bridge’s main arch, rendering it useless.

There is evidence (Zawadsky, 1929) that on at least two occasions local construction workers tried to rebuild it, but with no satisfactory results given that in both cases, upon removing the wooden trusses placed under the vault, the materials fell and were dragged away by the river. It was not till 1840 that Polish engineer, Estanislaw Zawadsky, directed the definite reconstruction work of the bridge.

2.3 Current state of conservation

A visual inspection carried out in 2006 permitted verifying that the bridge has not been altered by recent structural interventions, except for the restitution of the roadway surface in asphalt. A masonry plasterwork made with Portland-type cement mortar during the first half of the 20th century is in poor state of conservation (Fig. 5) and only remains on the upper portion of the bridge’s tympanums. On the lower part of the rings there is evidence of an accelerated degradation process of the bricks by weathering of the clay-like material due to prolonged exposure to environmental humidity and to the presence of the type of vegetation found in tropical regions, which contributes to the concentration of distinct living organisms upon bridge surfaces (Fig. 6).

The macro structure is still in service to vehicular traffic up to 5 Tons, as indicated to users. Maintenance work is necessary, as is the replacement of ceramic pieces that have disappeared by using new materials with similar physical and mechanical properties to those used in its construction.

3 CHARACTERIZATION OF THE CERAMIC PIECES ON THE BRIDGE

3.1 Mechanical properties

According to the results of the historical research, the bricks on the bridge over the Cauca River were made in artisan manner with local clays as raw material, the same craftsmanship still used in the fabrication of all types of pieces, with \(40 \times 20 \times 10\) cm standard dimensions. The furnaces are still simple constructions that use a combination of mineral coal and vegetable lumber as fuel, reaching firing temperatures between 750 and 1100°C. Production periods for the bricks vary between 8 and 12 days.

Due to analysis of specimens obtained from direct extraction of the masonry of the bridge, it was possible to perform physical and mechanical characterization of the clay pieces by following recommendations contained in the ASTM C133-97 (American Society for Testing and Materials, 2003) norms. Some of the results obtained in seven of the samples are shown in Table 2.

In spite of its low resistance capacity, there is no physical evidence of fissures or crushing caused by compression efforts.
Table 2. Results of the cold compression test applied samples taken from bricks on the bridge in Popayán over the Cauca River.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Maximum load (kN)</th>
<th>Resistance to cold crushing modulus (Mpa)</th>
<th>Elasticity modulus (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.96</td>
<td>5.07</td>
<td>208.30</td>
</tr>
<tr>
<td>2</td>
<td>7.89</td>
<td>4.94</td>
<td>96.58</td>
</tr>
<tr>
<td>3</td>
<td>29.58</td>
<td>9.19</td>
<td>232.88</td>
</tr>
<tr>
<td>4</td>
<td>19.57</td>
<td>6.04</td>
<td>144.66</td>
</tr>
<tr>
<td>5</td>
<td>6.92</td>
<td>2.78</td>
<td>87.48</td>
</tr>
<tr>
<td>6</td>
<td>21.29</td>
<td>7.53</td>
<td>171.85</td>
</tr>
<tr>
<td>7</td>
<td>10.88</td>
<td>4.14</td>
<td>89.67</td>
</tr>
</tbody>
</table>

*Source: Materials Resistance Laboratory, Universidad Nacional de Colombia at Manizales.

Figure 7. SEM/EDX micrograph (162x) of the organic portion of the surface of the construction work. Source: Plasma Physics Laboratory, Universidad Nacional de Colombia at Manizales, Colombia.

Other physical analyses carried out permitted concluding that the bricks on the bridge have high porosity (39.4–40.4%), which could not always be a characteristic of the original sample, but could be related to natural physical wear and to the environmental conditions.

3.2 SEM analysis

Scanning Electron Microscopy (SEM) micrographs with 162x magnifications (Fig. 7) applied over surface planes of the bricks reveal hyphae and the formation of mycelium of the fungus that has grown due to long-term environmental exposure. The porosity of the bricks facilitates the presence of these organisms.

Visual inspection permits deducing that the most affected areas are found on the borders of the structure and are probably caused by the incompatibility of the mortar joints with the bricks, along with the water percolation effect for many years.

Simultaneously, SEM analysis techniques were applied on samples extracted from an inner portion of masonry located at the base of the main arch of the bridge. This analysis permitted a first approach to understanding the structural characteristics of the material. The results obtained from one of the samples are expressed in Figure 8, and also related on Table 3. Silica and oxygen contents are notable in the total weight of the sample, slightly close to elemental content of the material currently used in the production of ceramics.

3.3 XRD analysis

A study of the mineralogical composition of three masonry samples was conducted via X-ray Diffraction (XRD) tests to identify the origin of the raw materials,
Table 4. Quantification of crystalline phases present in the samples via XRD.

<table>
<thead>
<tr>
<th>Compound</th>
<th>% of compounds in sample 1</th>
<th>% of compounds in sample 2</th>
<th>% of compounds in sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz, low</td>
<td>4.28</td>
<td>24.98</td>
<td>17.59</td>
</tr>
<tr>
<td>Trydimite</td>
<td>27.46</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Cristobalite, Low</td>
<td>44.2</td>
<td>45.57</td>
<td>52.98</td>
</tr>
<tr>
<td>Hematite</td>
<td>–</td>
<td>3.89</td>
<td>–</td>
</tr>
<tr>
<td>Paligorskyte</td>
<td>4.07</td>
<td>9.6</td>
<td>6.64</td>
</tr>
<tr>
<td>Anorthite</td>
<td>15.08</td>
<td>6.7</td>
<td>0.47</td>
</tr>
<tr>
<td>Muscovite</td>
<td>–</td>
<td>–</td>
<td>22.32</td>
</tr>
<tr>
<td>Barrerite</td>
<td>4.91</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Potassium Sulfate</td>
<td>–</td>
<td>9.26</td>
<td>–</td>
</tr>
</tbody>
</table>

*Source: Materials Resistance Laboratory, Universidad Nacional de Colombia at Manizales.

The results of these tests are shown in Table 4. All the brick samples manifest the presence of crystalline phases in different proportions of quartz, cristobalite, paligorskyte, and anorthite. The high level of quartz in sample 2, associated to its dark color and to the combination of cristobalite can be attributed to the presence large quartz particles (Rice, 1987).

The presence of cristobalite, associated to the orange hue of the bricks, indicates burning temperatures of at least 1200°C. Anorthite is a calcium feldspar, formed by the interaction of calcite decomposition residues (CaCO₃) and clay minerals during the burning process of the raw material upon reaching approximately 900°C, leading us to believe that for the sample analyzed the burning temperature was not above 1000°C (Cardiano et al. 2004). Nevertheless, the presence of hematite, which appears around 850°C, is the most valuable indicator of the burning temperature (Moropoulou et al. 2003).

4 DESCRIPTION OF THE BRIDGE’S MECHANICAL BEHAVIOR

A static analysis – due its own weight – and a modal analysis, both based on the behavior elasticity hypothesis of the masonry materials on the bridge, were conducted prior to its analysis against seismic forces. The ANSYS© v.10 software was used as the analysis tool. The elaboration of the model was done in four stages: (a) geometric reconstitution from AutoCAD© models, (b) grid-work of the model, (c) assigning of the properties of the materials, restrictions, and loads, and (d) solution of the model with emphasis on its static and dynamic analysis.

Initially, a complex model of the bridge was drawn up in 3D (67742 nodes and 33045 solid95-type elements), analyzing its structural response per its own weight. A series of geometric conditions for its static and/or dynamic conditions were accounted for: (1) displacements were null in the direction of the main axis, due to longitudinal confinement, (2) displacement in the transversal direction to the main axis of the bridge was equal to zero (as an effect of the wing walls of the bridge and the cutwaters located at the base of the piers), and (3) in the lower supports, all displacements were considered restricted. Numerical modeling was formulated from three structural components: the vaults, the tympanums, and the filler material.

4.1 Static analysis (analysis of the global behavior of the bridge)

The model of the bridge under gravity forces due to the weight of its own structure is shown in Figure 9. Crushing forces predominate with approximate values of 160.5 Kpa along the entire upper zone. In the lower zone, the crushing force value is greater, reaching values close to 1300 Kpa. Tension efforts are only present on the arches with values close to 422 Kpa.

Along the length of the longitudinal axis or the X axis there is a distribution of efforts with a certain degree of uniformity: in the zone between arches there are tensions with approximate values of 30 Kpa, while on those same zones in the lower part of the bridge the crushing forces reach values of 500 Kpa.

On the transversal axis, or the Y axis there is a predominance of crushing forces that vary from 200 Kpa to 400 Kpa, reaching a highest value of 750 Kpa below the arches. Small crushing phenomena are present on the lateral part of the bridge with values oscillating between 360 Kpa and 640 Kpa. The greatest displacement of the bridge, due to its own weight, is noted on...
4.2 Modal analysis modal (preliminary dynamic analysis)

Modal analysis of the bridge was conducted to identify its dynamic properties. For such, the first 10 vibration modes were obtained. Figures 10–12 show the first, third, and tenth mode of vibration, with modal frequencies of 1839 Hz, 2148 Hz, and 3138 Hz, respectively.

It can be stated that the components with the greatest contribution to the total displacement of the bridge for each vibration mode are those corresponding to the transverse Y axis and the perpendicular Z axis. On the Y axis, the greatest displacement occurred on the sixth vibration mode – reaching a displacement close to 8.20 cm, and for the vertical Z axis displacement occurred on the ninth vibration mode with a value of 26.9 cm.

The greatest total displacement is caused on the ninth vibration mode, presented on the span of the main arch with a value near 27.2 cm with a domain in the direction of the vertical axis of the bridge at 26.9 cm. Hence, under dynamic conditions, the ninth modal form represents the greatest risk to the structural integrity.

4.3 Seismic analysis

To simulate the response of the bridge to seismic effects, we used a seismic spectrum given by Colombian norm NSR-98 (Colombian Association of Seismic Engineering, 2002) given by the equation:

\[
\begin{align*}
S_a(T) &= \frac{25}{3} A_a IT \frac{\sqrt{g}}{T} T \leq 0.3 \\
&= 2.5 A_a I \frac{\sqrt{g}}{T} 0.3 \leq T < 0.48 \\
&= 1.2 A_a SI \frac{\sqrt{g}}{T} 0.48 \leq T \leq 2.4S \\
&= \frac{A_a I}{2} \frac{\sqrt{g}}{T} T \geq 2.4S
\end{align*}
\]

where \( A_a \) = the parameter defining the maximum acceleration in the region during a 475 year time lapse; \( S \) = the parameter defining the type ground under the structure; and \( I \) = the parameter defining the importance of the edification according to a possible seismic disaster. The following values were adopted in this analysis: \( A_a = 0.25 \); \( S = 1.5 \); \( I = 1.2 \).

As a main result, it can be said that upon seismic incidence defined by the spectrum mentioned, the zone with the greatest structural vulnerability is the main arch of the bridge, herein experiencing tension forces that reach maximum values near 5298 Kpa with its main component in the positive direction of the vertical axis of the bridge, as noted in Figure 13. That is, in its dynamic condition, the bridge mainly experiences
tension phenomena with values around 75% above the maximum crushing values presented by its static condition, aside from such forces being concentrated in the zone of the main arch.

5 CONCLUSIONS

We have discovered the existence of a coincidence relationship amongst the questions: what does it mean and how does it behave, which can only be answered by also knowing the: how is it? In this sense, is that the methodological aim stems from a detailed description of the bridge studied. The “how is it” is answered by defining three fundamental aspects: (a) the shape, understood as all that is susceptible to being graphically expressed and keeps a close relationship with the historical genesis of the building, (b) the matter, i.e., the description of the mechanical properties (physical/chemical), and (c) the structure, understood here as the system of relationships among the materials and the shape.

Herein, we consider that research conducted on historical buildings (edifications) should be developed around those three spaces: the first of these through field work involving architectural drawings, historical documentation, and visual inspection. Work on the study of materials is carried out with the aid from laboratories that have reported results, which have been employed in the numerical modeling process via the method of finite elements, seeking to understand their behavior.

Easy access to calculus computer programs has made the Method of Finite Elements (MFE) an applicable path in the study of historical edifications. There is abundant bibliography on the issue, as well as case studies where the MFE has been applied. One of the great advantages is that, additionally, it permits answering a fourth question: how will it behave? This is an important nucleus of the problem: foresight of the interrelationships between the existing object and the different alternatives to intervene upon it and how to obtain a guarantee in each of them.

Thus, precisely knowing the behavior modes, understanding their matter, and predicting the types of responses to future actions are today the indispensable means of intervention upon the historical patrimony. The research project exposed here points, in the long term, toward the concrete design of actions leading to the recovery and adaptation of the greatest possible number of cases, involving the work of local communities.

ACKNOWLEDGEMENTS

The authors thank the support of the Dirección de Investigaciones (DIMA) at Universidad Nacional de Colombia in Manizales, for the financial support to carry out this project. The authors also recognize the collaboration received from professors A. Devia and O. Correa from the same institution.

REFERENCES


