Brick arch bridges in the High Cauca Region of Colombia (1718-1919)

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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 carried out with three of them and conclusions are presented, which can be extended to almost the totality of the cases studied for the purpose of offering new analysis alternatives to professionals interested in the rehabilitation and conservation of the Colombian architectural and engineering patrimony.

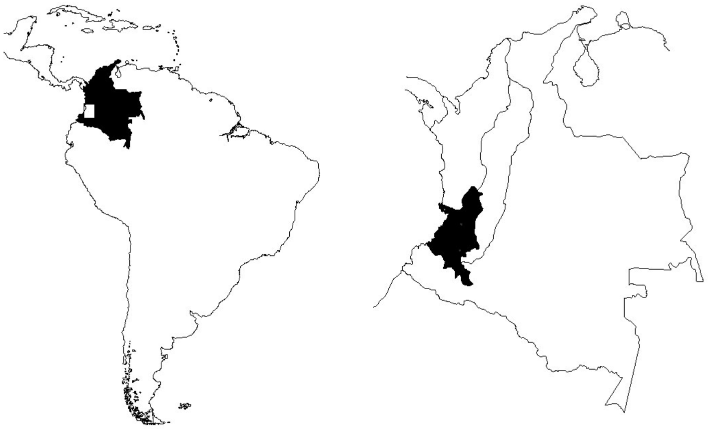
1 INTRODUCTION

Throughout the 18th and 19th centuries, along a land surface of two thousand kilometers situated in the High Cauca geographical region of Colombia, flourished a construction tradition with deep Mediterranean roots related to the preparation of construction materials (bricks and mortars), the fabrication of centerings, the laying of rings, the dimensioning of piers, and, in general, all that related to the conformation of brick arch bridges; structures that have been preserved notwithstanding the difficult conditions of their natural and social environment and of the strong and intense seismic activity in the zone where they are located.

Given the magnitude of the inventory upon which the investigation develops, this presentation will only refer to three, which correspond to those that (a) possess dimensional characteristics that separate them from the rest, and (b) that are today still in service to vehicular traffic, making them vital parts in the regional infrastructure. These are: (a) the bridge over the Cauca River in the city of Popayán, (b) the bridge over the Güengüé River, on the road that unites the municipalities of Corinto and Miranda, and (c) La Libertad Bridge over the Guadalajara River in Buga.

The first phase of the investigation enquired in documental sources as to the origin of each of them; thereafter, an architectural rendering was conducted in order to know their geometries and dimensions; a third phase manager to make a physical-chemical characterization of their essential materials (brick and mortar); and a fourth activity has sought to understand their mechanical behavior, making use of a commercially available finite element package.

It is important to note that although in Europe much work had already been oriented at understanding the strength capacity and the conservation and/or restoration possibilities of these types of structures, in Colombia – to date – there are no studies aimed at trying to aid in understanding their importance and historic value. The long-term objectives of this work are aimed in that direction and have set out, as a first assignment, to appropriate and develop a methodology that leads not merely to the integral understanding of the constructed object, but that allows establishing action guidelines upon the constructed patrimony.



Figures 1 and 1a : Location of the area of investigation.
Colombia in the South American continent – The High Cauca region in Colombia.

2 GENERAL DESCRIPTION OF THE BRIDGES UNDER ANALYSIS

The three bridges are part of the road that since colonial times linked Popayán (founded in 1637 and as of then the regional capital), with other towns following a north – south direction along the Cauca River Valley. Agricultural and mining products circulated upon this route, making this region one of the richest in western South America.

2.1 Bridge over the Cauca River in Popayán

It was built between 1769 and 1773 by local master builders from plans drawn up by German priest, Father Schenher. It is 153 meters long and has a potent half-point arch 19.06 meters in diameter (main arch) which spans the Cauca River. Three leveling arches, also of half point, give the slope on the northern side; while on the southern side the central arch is supported directly over a buttress interlocked into a natural terrain wall.

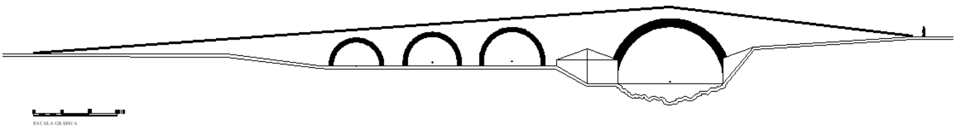


Figure 2: Rendering of the bridge over the Cauca River in Popayán.

The bridge, with a constant 5.84-m width in its length, is entirely made of brick cemented with lime mortar; although rows of wrought stone – occasionally appearing as construction material on the spandrel walls – are noted beneath the central arch. A sole diamond-shape cutwater is found bellow the extreme north of the main arch.

Table 1 : Measurements and dimensional relationships of the bridge over the Cauca River in Popayán.

Element	Diameter of the arch m	Width of the rings m	Ratio width of ring / Diameter of the arch -	Width of the piers m
Arch 1	8.47	0.76	0.08	
Arch 2	9.00	0.78	0.08	
Arch 3	10.35	0.77	0.07	
Arch 4	19.06	1.48	0.07	
Pier arches 1 – 2				4.97
Pier arches 2 – 3				4.78
Pier arches 3 – 4				13.98

Note : the numbering of the arches has been done from left to right as per Figure 2.

2.2 *Bridge over Güengüé River between Corinto and Miranda*

Its construction was carried out between 1893 and 1897 by local construction masters: Rafael González Concha and Antonino Olano.

It has 8 half-point arches situated under a double-slope. Under such, which are symmetrical and reach a 10.02-m span, there is the flow of the river. It has three triangular vertex cutwaters that have recently been reconstructed in reinforced concrete.

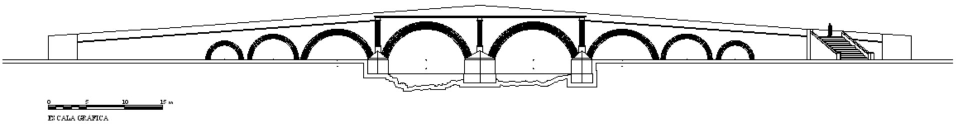


Figure 3 : Rendering of the bridge over the Güengüé River.

It is 4.8 m wide and it is entirely built of brick cemented with lime mortar. Footpaths with steps were constructed at its two extremes for pedestrian traffic, but one of these has been demolished.

Table 2 : measurements and dimensional relationships of the bridge over the Güengüé River

Element	Diameter of the arch m	Width of the rings m	Ratio width of ring / Diameter of the arch -	Width of the piers m
Arch 1	3.79	0.76	0.20	
Arch 2	5.58	0.78	0.13	
Arch 3	8.0	0.77	0.09	
Arch 4	10.02	1.48	0.14	
Arch 5	10.02	1.48	0.14	
Arch 6	8.09	0.77	0.09	
Arch 7	5.58	0.78	0.13	
Arch 8	3.79	0.76	0.20	
Pier arches 1 – 2				1.71
Pier arches 2 – 3				1.62
Pier arches 3 – 4				2.51
Pier arches 4 – 5				3.87
Pier arches 5 – 6				2.51
Pier arches 6 – 7				1.62
Pier arches 7 – 8				1.71

Note : the numbering of the arches has been done from left to right as per Figure 3.

2.3 La Libertad Bridge over the Guadalajara River in Buga

It was constructed over a 27-year period and completed in the year 1900 under the direction of one of the first Colombian engineers trained in the country: Modesto Garcés.

In a first phase of the construction, three huge brick and lime mortar arches were raised over the Guadalajara River bed. Each of the three half-point arches has a span of 9.51 m with variable section rings between 0.95 m at the keystone and 1.82 m at the spandrel. Thereafter, at an unspecified date, but prior to it being put to use, leveling viaducts were built: the one on the north side has 9 half-point brick arches of variable span, and the one on the south side has only 3 variable-span arches. Galindo (2003).

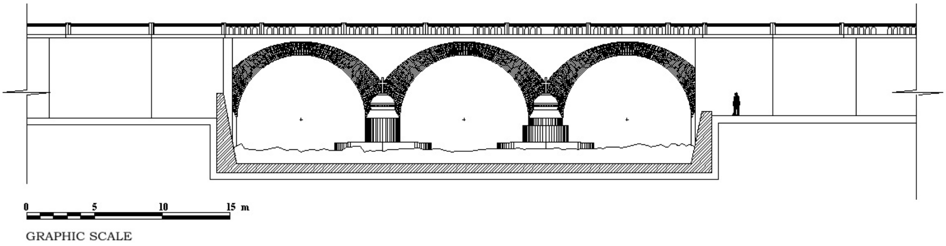


Figure 4 : Rendering of the central portion of the La Libertad Bridge.

It has a constant width of 6 m; although during the second half of the 20th century, its width was brought to 8 m by an addition of overhanging concrete beams at each side. The two central piers founded over the river have corresponding cutwaters of semicircular vertex.

Table 3 : Measurements and dimensional relationships of the La Libertad bridge

Element	Diameter of the arch m	Width of the rings m	Ratio width of ring / Diameter of the arch -	Width of the piers m
Arch 1	9.51	0.95	0.1	
Arch 2	9.51	0.95	0.1	
Arch 3	9.51	0.95	0.1	
Pier arches 1 – 2				2.53
Pier arches 2 – 3				2.53

Note : the numbering of the arches has been done from left to right as per Figure 4.

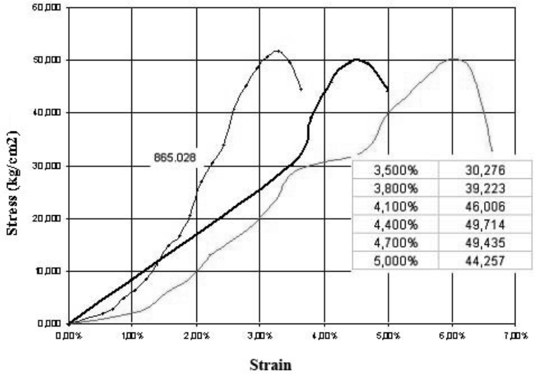
From the comparative analysis of the dimensions of the three bridges, it is not possible to confirm the existence of a geometric pattern dictating principles of constructive nature. Notwithstanding the structures constructed within the same context, each bridge was assumed as a problem to be solved independently. The absence of a sound construction tradition and the lack of continuity in the cultural processes can be an explanation of such.

3 CHARACTERISTICS OF ITS CONSTRUCTION MATERIALS

Once historic information was obtained on each of the bridges and artistic renderings were conducted, samples were collected of their construction materials (brick and mortar) through the extraction of nuclei in all three cases (in rings and spandrel walls) and a whole brick piece from the bridges in Popayán and Güengüé. In the case of the filler material, it was not possible to get reliable samples given their granular condition, making it necessary to conduct a manual perpendicular drilling over the surface of the bridge in Caloto, whose construction dates to 1906 and is located in a geographic point that is equidistant to the three bridges adopted as case study.

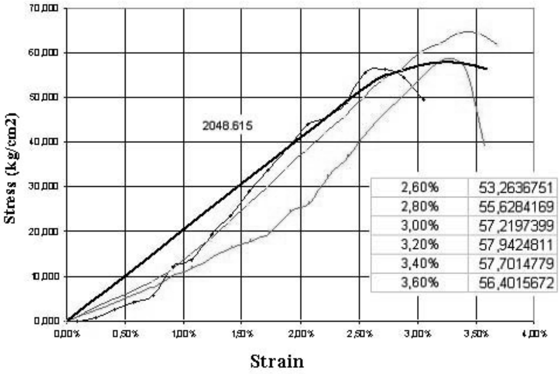
3.1 Mechanical characterization of the bridges

Each of the samples obtained from the bridges underwent a set of laboratory tests following recommendations established under Norm NTC 682 by Instituto Colombiano de Normas Técnicas y Certificación, (2000), equivalent to the ASTM C 133/97 Norm. Through said tests, significant data was obtained: (a) compression resistance, (b) module of elasticity, (c) rupture module, and (d) maximum deflection.



3,500%	30,276
3,800%	39,223
4,100%	46,006
4,400%	49,714
4,700%	49,435
5,000%	44,257

Figure 5 : Stress curves – unitary deformation corresponding to 2 samples taken from the bridge in Popayán.



2,60%	53,2636751
2,80%	55,6284169
3,00%	57,2197399
3,20%	57,9424811
3,40%	57,7014779
3,60%	56,4015672

Figure 6 : Stress curves – unitary deformation corresponding to three samples taken from the bridge over the Güengüé River.

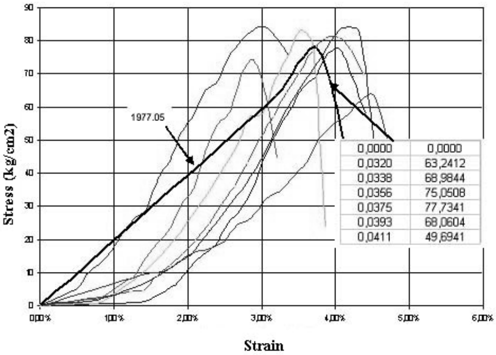


Figure 7 : Stress curves – unitary deformation corresponding to seven samples taken from the La Libertad Bridge.

To obtain the unitary deformation effort curve of the characteristic material, the linear and non-linear range was determined initially for each sample of the bridges and, then upon some of the points corresponding to the non-linear zone; the average was calculated for the values of unitary deformation, as well as for the stress on the number of samples. With the inelastic region of the curve defined, the elastic region was calculated as the slope of the straight section that unites the origin to the first point of the inelastic zone.

The strong variation in the values of the modules of elasticity and the points of fluency, even from the same bridge and the same sample, evidencing the heterogeneity of the properties of the bricks, is noted in Figures 5, 6, and 7. Furthermore, it can be seen that the stress curve – unitary deformation is approximately lineal within a given range, that is, it permits supposing that the material that makes up the arches and the spandrel walls reveals elastic lineal behavior. Additionally, after the yield point the curves show a very similar pattern for the plastic range in each of the bridges.

3.2 *Mechanical characterization of the mortars*

The very conditions of the mechanical extraction of nuclei did not allow for valid samples of mortars in any of the three bridges analyzed. However, given that the historic research managed to have precision upon the origin of the limes (quarries in the municipality of Vijes) and the sands (river bed of each river), a mix of the mortar was simulated in the 1:3 proportion, which was subjected to mechanical tests to obtain two significant data: (a) compression strength and (b) module of elasticity.

3.3 *Chemical characterization of the bricks*

Three brick samples were extracted from the bridge in Popayán. These were subjected to X-ray diffraction (XRD) tests, evidencing the regular presence of quartz, cristobalite, and palygorskite, as well as reaffirming the highly heterogeneous characteristic of the samples; although belonging to the same bridge.

Table 4 : Quantification related to crystalline phases present in the 7151/52/53 brick samples

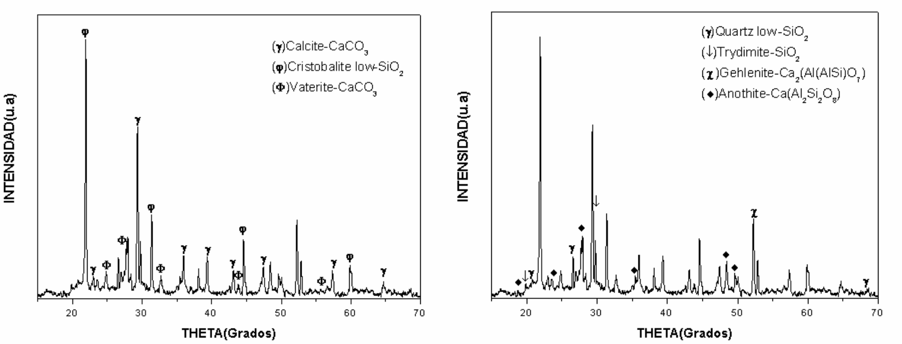
Name of compound	Chemical formula	Percentage related to the 7151 sample	Percentage related to the 7152 sample	Percentage related to the 7153 sample
Quartz, low	$SiO2$	17.59 %	24.98%	4.28 %
Anorthite	$Ca(Al2Si2O8)$	0.47 %	6.70%	15.08 %
Cristobalite. Low	$SiO2$	52.98 %	45.57%	44.20 %
Palygorskite	$(Mg2.074Al1.026)(Si4O10.48)2(OH)2(H2O)10.68$	6.64%	9.60%	4.07%

Muscovite	KAl3Si3O10(OH)2	22.32%		
Potassium Sulfate	K2SO4		9.26%	
Hematite	Fe2O3		3.89%	
Trydimite	SiO2			27.46%
Barrerite	Ca2(Al(AlSi)O7)			4.91%
TOTAL		100%	100%	100%

The same conclusions are reached from the analyses of the samples of the bricks taken from the Güengüé and Buga Bridges.

3.4 Chemical characterization of the mortars

A granular-state sample of the mortar from the bridge in Popayán was subjected to an X-ray diffraction (XRD) test to conduct a quantitative and qualitative analysis of the crystalline phases of its characteristic components, be they inorganic or not and, specially, to determine the inert nature of its ligants.



Figures 8a and 8b : X-ray diffraction analysis (XRD) on (7159) mortar sample
Spectrum of X-ray diffraction. Intensity in arbitrary units in function of 2θ. Figures show intensities and diffraction angle for the crystalline phases of the remaining compounds found to make up the mortar sample.

The XRD analysis evidenced the high percentage of silicium present in the mortar sample and permitted observing the crystalline phases of the low quartz (12.38%), the tridimite (10.65%), and the low cristobalite (9.06%); compounds attributed to the presence of sand in the sample. The crystalline phases of the vaterite (crystalline phase of calcium carbonate, 6.66%) and the calcite (44.96%) are also referenced in the XRD spectrum and attributed to the presence of lime in the sample.

Table 5 : Relative quantification of crystalline phases present in the 7159 mortar sample

Name of compound	Chemical formula	Relative percentage
Quartz,low	SiO2	12.38 %
Trydimite	SiO2	10.65%
Anorthite	Ca(Al2Si2O8)	6.88 %
Calcite	CaCO3	44.96%
Cristobalite.low	SiO2	9.06 %
Vaterite	CaCO3	6.66%
Gehlenite	Ca2(Al(AlSi)O7)	9.41%
TOTAL		100%

As in similar studies -Moropoulou et al. (2000)-, calcite is the main component of the matrix and it is identified as the typical ligant of the mortars.

As per the morphological aspects of the mortars, differences in textures were found in color, and consistency, which can be due to the zone's variable geology.

4. STRUCTURAL CHARACTERIZATION

The structural analysis of constructed sites is a complex task; the heterogeneity of the materials makes any generalization difficult and, in practice, there is no particular generalized analysis method for these types of structures. Hughes and Blacker (1997). Using, in practice, methods ranking from the very simplified to the complex non-lineal models based on the Finite Elements Methods with elastic-plastic behavior of the materials and including elements that characterize the joints and the interfaces.

For the most part, the prior analyze the capacity of the bridge only in the longitudinal sense; however, many of the faults appear in the transverse sense due to the effects of the pressure upon the surface or the presence of fissures transversely -Fanning et al. (2001)-, as evidenced by the bridges studied.

For this stage of the research, analysis was conducted of each bridge as a macro model using – in function of its possibilities and versatility – the ANSYS v.10 software, which has a solid-type element; particularly, solid95 and solid65 that permit modeling structures in three dimensions, and tolerates irregular shapes without losing precision and offers possibilities of modeling curved surfaces; they also permit using materials with elastic-plastic characteristics, as well as including in the analysis the behavior curves obtained in the laboratory tests.

Several stages were followed in carrying out the models of each of the three bridges: (a) geometric reconstruction from the drafts elaborated in AutoCAD to be exported to the ANSYS v.10 software, (b) grid-work of the model, (c) assignation of the properties of the materials, restrictions, and loads, and (d) final solution of the model.

For the purpose of simplifying the exposition, only the case of the La Libertad Bridge in Buga was presented.

4.1 Preliminary numerical analysis

A simplified three-arch model was carried out according to the very geometry of the bridge, assuming the following considerations in the boondary conditions.

On the vertical faces of the extremes of the bridge's main axis, note: (a) null displacements in the direction of the main axis, by longitudinal confinement, (b) the displacement in transversal direction to the bridge's main axis is equal to zero (initial consideration in state of verification), (c) displacements in the free vertical sense to give continuity to the movement of the bridge in its complete model.

In the lower supports, all displacements are considered restricted (condition of support).

For numerical modeling, three types of materials were used, one for each of the structural parts that make up the bridge: ring, spandrel wall, and filler material, as explained in Table 6 and following the analysis guidelines applied in structural in similar structures. Frunzio, et al. (2001).

Table 6 : Characteristics of the materials of the construction parts of the La Libertad Bridge in Buga

Structural element	Unitary Weight kN/m^3	Poisson Coefficient -	Elasticity Module kPa
Ring of the arch	2200	0.45	3x109
Spandrel wall of the bridge	2200	0.45	2.5x109
Filler Material	1700	0.45	1.5x109

Considering that the programs of finite elements do not have a particular module of unit conversion, the data was input in consistent units. For this case, considering the acceleration of gravity by $10 m/s^2$, the unitary weight of the materials will be expressed by kN/m. The resulting stresses are obtained by kN/m^2 (kPa), the displacements by meters and the forces by kN.

For the sake of simplicity, only the value of dead weight was considered. The wing walls of the bridge were not contemplated. The resistance of the masonry was calculated through Mann's Formula -Hendry (1998)- and the Drucker-Prager Concept was assumed as a rupture criterion for the filler material using cohesion values c=30 kPa, an angle of internal friction f=32º, and a dilatance angle b=16º.

In the grid-work process and for the purpose of reaching continuity of the elements, the nodes of all these are made to coincide; notwithstanding that they belong to different solids. A better-organized grid work was managed from the use of hexaedrals, creating – furthermore – elements of similar lengths in the perimeter of each area; for this case a 40 – 50cm length was chosen.

4.2 *Graphs of displacements and longitudinal stress*

The software used permits visualizing the displacements and the stress distribution in the macro model in any of the three axes of spatial coordinates (x, y, z), as well as quantifying the value of maximum loads.

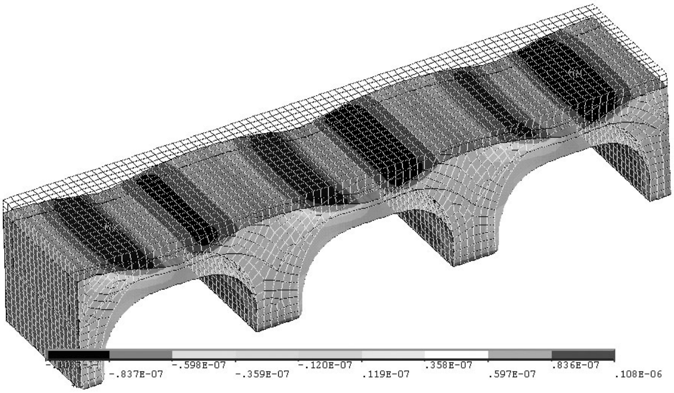


Figure 9 : Displacements in X direction.

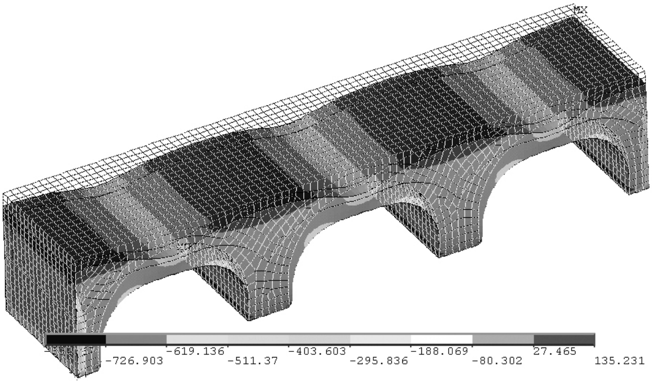


Figure 10 : Stress in X direction

On the bridge, the value of the maximum load is lower than the resistance capacity of the masonry, which confirms that the material does not fail and is not a cause of a possible collapse situation. The loss of equilibrium due to seismic action or instability of the piers due to a river surge would be the cause of a global failure.

The symmetry of the structure, both longitudinally and transversely, simplifies its general behavior.

A detailed visual inspection of the La Libertad Bridge confirms its good state of conservation. However, studies soon to be conducted and aimed at monitoring vehicular traffic upon the bridge will allow for a more complete diagnosis.

5 CONCLUSION

A relationship of coincidence was discovered between the questions: how does it behave, and what does it mean, which can only be answered after having clarity of how it is. In this sense, is that the methodological approach sets off from a detailed description of each of the historic bridges mentioned. "How is it", is answered by defining three fundamental aspects: (a) shape, understood as all that susceptible of being graphically expressed, (b) matter, that is, the description of the mechanical properties and, whenever possible, the physical and chemical properties, and (c) structure, understood here as the system of relationships among the materials and the shape.

Currently, the research acts upon those three environments, having completely conducted the first one through field work that involved architectural renderings, historic documentation, and visual inspection. The task of the study of the materials is being carried out with the aid of the Materials and Plasma Physics laboratories at Universidad Nacional de Colombia, in Manizales. With the data from these laboratories, a process of numerical modeling was conducted via the method of finite elements in hopes of understanding their behavior.

The easy access to programs of computer-based calculations has made the Method of Finite Elements an applicable road for the study of historic edifications. There is abundant bibliography on the issue, as well as case studies on the Method of Finite Elements that has been applied. One of its great advantages is that, additionally, it permits answering a fourth question: How will it behave? This is an important nucleus of the problem: to foresee the interrelationships between the existing object and the different alternatives to intervene upon it and how to reach the warrantee in each of them.

Knowing precisely the modes of behavior, understanding its matter, and predicting the types of response to future actions, are today the indispensable means for intervention on historic goods. The research project highlighted here aims at, in the long term, the concrete design of actions geared at recovery and adaptation of the greatest number of possible cases, involving the work of local communities.

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