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# Survey, Digital Reconstruction, Finite Element Model of the Augustus Bridge in Narni (Italy)

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ABSTRACT: Through this multi-disciplinary research on the Augustus Bridge the authors intended to show a new way of approaching an ancient monument analysis, from all points of view, from the well-known and established disciplines, like historical and geographical ones, up to the new innovative subjects, like Computer Vision and Finite Element Analysis.

## 1 INTRODUCTION

It's well known that when heritage buildings are taken into consideration by architects and structural engineers, many other disciplines have to be analysed: its history and archaeological aspects, its geographical position, its building materials and their origins; in particular, the surveying and virtual reconstruction are basic. The following one is an example showing our methodology.

The so-called Augustus Bridge was a facility of the Roman Flaminia road. The consular road linked Roma and Ariminum, now Rimini, on the Adriatic sea, passing through Narnia, now Narni; the Bridge allowed the crossing of the Nera river valley. Narni is a town of Umbria, a region of central Italy not far from Rome.

Built probably in 27 B.C., during the consular roads extension works promoted by the emperor Augustus ("Consul Septimum viam Flaminiam ab urbe Ariminum refeci pontesque omnes praeter Milvium et Minucium" Augustus), it is one of the largest bridges, in stone voussoirs, ever constructed by the Romans: formed by four arches, it was about 160 meters long with abutments and piers. Now only one of the arches is still standing; its diameter is about 20 m. and its intrados keystone height is 23 m. (Fig. 1). The contiguous arch collapsed, according to historical sources, in XI century (Contratto): it had a span about 32 m. wide, a top record in Roman architecture (O'Connor 1993). The existing pier is about 10 m. wide and about 8 m. thick.

The masonry of the Augustus Bridge is composed of internal concrete filling, *opus caementicium* and of an external face made of travertine voussoirs, *opus quadratum*, that consists in alternative rows of "stretchers" 1-2 m. long, 0.6 m. high and 0.8 m. thick and "headers" 0.6 m. long, 0.6 m. high and 1-2 m. thick (Balance 1951)

Many researches were carried out into this subject from the sixteenth century. The main topics were:

- ✓ Archaeological and historical notes on the bridge, e. g. (Blake 1947) (Balance 1951), its rich iconography, e. g. (Corot 1826), its literary sources, e. g. (Martialis)
- ✓ the real shape of the Bridge, its arches and their dimensions (Eroli 1848)
- ✓ the architectural origin of the arch in the right side of the river which is ribbed as a modern one (Galliazzo 1995) (O'Connor 1993)
- ✓ the reasons why piers have no cut-waters (O'Connor 1993)
- ✓ the causes of the bridge failure (O'Connor 1993)

Our study pursues the exposed subjects too, but it differs from the former ones especially for the extensive use of the new modern digital and electronic technologies:
- ✓ the laser total station, a topographical instrument which can survey unreachable points, well suited to survey the ruins of the bridge
- ✓ the digital camera
- ✓ the stereo-restitution of digital images through the analytical techniques of the very new discipline, Computer Vision, as the use of the edge detector method to identify geometrical figures in a digital image (Canny 1983) (Faugeras 2001[4]) (Hough 1962) (Pratt 1991[2]), for virtual three-dimensional reconstruction
- ✓ CAD instruments
- ✓ non linear finite-element programs for the numerical approach to the mechanical model of the virtually reconstructed bridge (Bathe 1996) and of its collapse

In our research the results of these new technologies were always compared with the historical sources, the old iconography and the former studies.

Other sides, never taken into account before, were also considered:
- ✓ the river Nera and its affluent Velino whose courses and flows changed greatly during the many centuries from the building of the bridge: for example the Romans dug the “Cascata delle Marmore”, the highest waterfall of Europe, to let the Velino flow into the Nera.
- ✓ the geological aspects of Nera and Velino basins
- ✓ the chemical composition and the geological origin of the materials, travertine and concrete, of the bridge (Cantisani et al., 2002)
- ✓ the mechanical strength of both materials, travertine and concrete (Passetti 1997, Sinibaldi 1998)

Figure 1 : The standing arch of the Augustus Bridge

## 2 ANALYSIS OF THE RUINS

### *2.1 Survey of the Bridge*

#### *2.1.1 Topographical survey*

The survey was performed in the year 2002 through the use of an electronic total station, the Leica TCR 705 model, with 5” angular precision and 2 mm + 2 ppm linear precision, a digital camera Fujifilm Fine Pix S1 Pro, with a 6.1 Megapixel CCD and a 50/30 mm interchangeable Nikon® optics. The laser wave, in the TCR 705 total station, can survey points identifiable but not reachable up to a maximum distance of 100 meters.

The surveying process was performed using a four stations (fixed to the earth) mesh, linked together and to the topographical map 1:5000. Afterwards, from the four vertexes, other temporary stations were created and the detail measures were tracked (Fig. 2).

The mesh was referred to a Cartesian orthogonal reference system. Approximately 2000 points of the bridge and ruins were collimated. Most of these points were tracked directly, while twenty tokens, in order to increase the precision of the survey, were placed on the main arch, the abutments and the pier, with the help of a fire fighter car carrying an elevator.

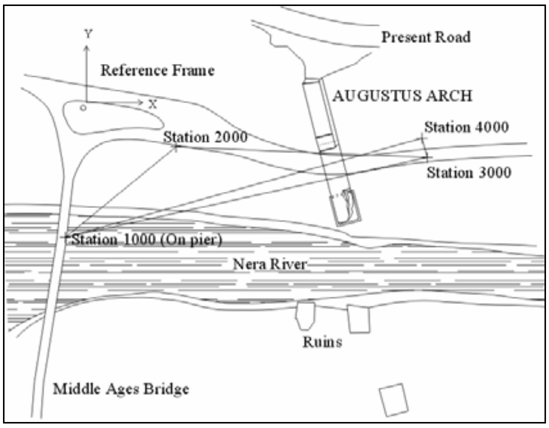


Figure 2 : Top view of the four fixed stations mesh, used in the survey of the Augustus Bridge

### *2.1.2 Photogrammetry and Computer Vision*

The 3D-space and objects modelling through images has recently widened the frontiers of photogrammetry, thanks to the new techniques in informatics and to the digital image: in particular great steps in this direction have been performed by means of a new discipline, *Computer Vision* (Faugeras 2001[4]) (Pratt 1991[2]), that studies the 3D-space referencing, in both static and dynamic environment.

The innovative techniques of this discipline have been applied to this *casus studii* and in particular they have been useful to solve the following problems typical of this discipline:

- ✓ Recognition of points, lines, geometric shapes out of a digital image;
- ✓ Recognition of the same points out of different digital images;
- ✓ 3D space recognition and reconstruction;

#### 2.1.2.1 Point identification

In order to identify points unequivocally in collimation and reconstruction phases, the Computer Vision techniques have been applied, using in sequence the *Edge Detector* (Canny 1983) and *Hough Transform* methods (Hough 1962).

These mathematical algorithms use an important physical quantity of the digital image: the luminance. Changes or discontinuities in luminance often provide an indication of the physical extent of the objects within the image. In particular the rate of change or the discontinuities of the luminance defines the edges of the shapes in the image. By this process it is possible to define some differential operators, called *Edge Detectors*, whose task is to search object boundaries in digital images. An edge is judged present if the gradient exceeds a defined threshold.

The single pixels that represent the object boundaries must be grouped. Therefore it will be necessary to build a database of recognizable shapes and compile for each one a different algorithm.

The most used method in elementary shape searching and recognition is certainly the *Hough Transform* introduced in 1962. Hough algorithm pays attention to build a parametric space, defined by a n-dimensional array, inside which all the points of the binary image belonging to a particular curve are stored and accumulated.

The main feature of the Hough Transform technique is the isolation of a particular shape within a digital image: since in input the Hough Transform algorithm requires that the searched shapes have to be expressed through a parametric curve, the classic formulation is commonly used to identify objects referable to a regular curve, like straight lines, circumferences, ellipses.

#### 2.1.2.2 Same points identification out of different digital images: the correlation function

In the stereoscopic process, the recognition of the same point out of different image is fundamental for an accurate object reconstruction. In order to achieve this goal, it is possible to use the information from a digital image, working both on their geometric relationship and grey levels. Selected a point on the first image, the other images are compared with the first one and the coefficient of correlation calculated: the maximum value of the coefficient represents the point found on the other images (Faugeras 2001[4]).

2.1.2.3 Stereo restitution

Finally, according to the Computer Vision and photogrammetry described methods, the acquired digital images have been calibrated through the surveyed points and the Augustus Bridge three-dimensional real shape have been reconstructed (Figs. 3-5).

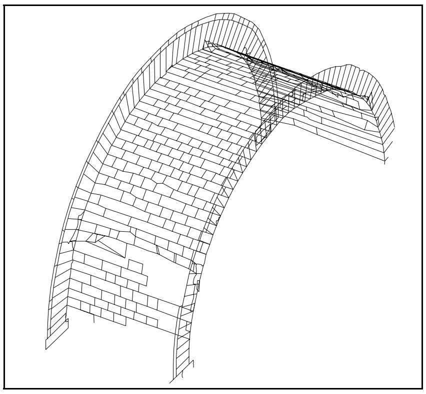

Figure 3 : Three-dimensional standing arch stereo restitution

### *2.2 Materials: concrete and travertine*

The analysis on the materials that form the Augustus Bridge shows a great attention of the Roman workers in choosing stones for masonry and basic elements for mortar production. (Cantisani et al.n2002).

#### *2.2.1 Chemical and Physical aspects*

2.2.1.1 Concrete

The masonry sac has been realized with regular footwall distribution of mortar. This kind of mortar has an excellent cohesion and adhesion to travertine ashlars. These particular features are due to the high hydraulicity of the binder, even higher to that of Portland concrete. But this kind of hydraulicity has not been obtained as usually with the addition of special additives like pozzolan or diatomaceous earth; on the contrary it seems due to the use, as a water lime stone, of the local chert limestone.

2.2.1.2 Travertine

In building the ashlars of masonry, a dense, solid and not so porous travertine has been chosen.

The choice of this kind of lithotype, instead of other carbonate rocks that were near the Bridge, can be explained as the travertine could be shaped and modelled in regular blocks, thanks to presence of layers of the suited and desired thickness. In the neighbourhood of the bridge there are important travertine formations: for example the archaeological area of Carsulae stands upon a formation like this, but the Belemitella Americana tests did not show this origin.

#### *2.2.2 Mechanical features of the materials*

For a better comprehension of the structural behaviour of the Augustus Bridge, it has been necessary to understand the mechanical features of the used materials in building the bridge. The campaign of tests has been realized by the university of Perugia (in the I.S.R.I.M laboratory of Terni). The UNI EN 1926 standards has not been perfectly applied, because of the problem of the material acquisition, as the monument is an ancient one, protected by the Italian law on archaeological sites.

2.2.2.1 Concrete

The tests on concrete provided its mechanical characteristics, and in particular, its compression tensile stress, its Poisson coefficient and its coefficient of elasticity. Then the density of the binder has been computed.

For the compression test there have been used four test pieces. In Table 1 the results for each test piece of the compression ultimate tensile stress, of the Poisson coefficient and the coefficient of elasticity are shown.

Table 1: Tests on the concrete of the Augustus Bridge

| | $R_C$ (Mpa) | Poisson coefficient | E (GPa) |
|---|---|---|---|
| Test piece 1 | 26.5 | 0.1 | 7.7 |
| Test piece 2 | 20.0 | 0.2 | 14 |
| Test piece 3 | 30.0 | - | 15 |
| Test piece 4 | 22.0 | - | - |
| Medium Value | 24.62 | 0.15 | 12.23 |

2.2.2.2 Travertine

The tests on travertine provided its mechanical characteristics, and in particular, its compression tensile stress. Besides the specific gravity of travertine has been calculated.

For the compression test there have been used seven test pieces. In Table 2 the results for each test piece of the compression ultimate tensile stress are shown.

Table 2 : Tests on the travertine of the Augustus Bridge

| | $R_C$ (Mpa) |
|---|---|
| Test piece 1 | 20.69 |
| Test piece 2 | 13.58 |
| Test piece 3 | 28.03 |
| Test piece 4 | 29.47 |
| Test piece 5 | 31.75 |
| Test piece 6 | 10.09 |
| Test piece 7 | 14.78 |
| Medium Value | 21.20 |

## 3 VIRTUAL RECONSTRUCTION OF THE BRIDGE

### *3.1 Hypothesis on the shape of the Augustus Bridge*

According to Gautier (Gautier 1723) the Roman arch is a round one, or, more rarely, a depressed round one. In particular H. Gautier in his treatise shows this rule: “If a bridge is formed by arches of different diameter with their keystones at the same height, the springing of the wider arch on the piers must be at lower elevation in comparison with the elevation of the arches of smaller diameter, always preserving its round shape of the arch; or alternatively the arch is a depressed one, though still a round one.” As an example of this Gautier exemplifies the Pont du Gard (Fig. 4).

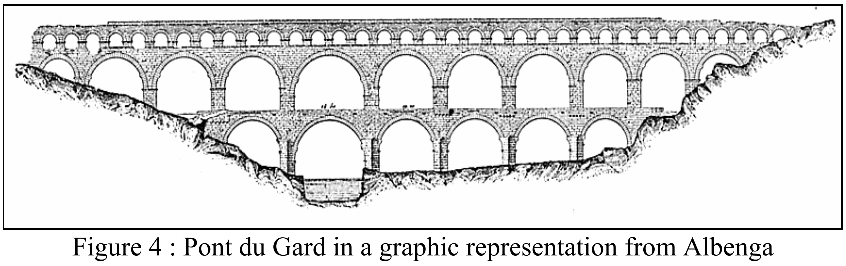

Figure 4 : Pont du Gard in a graphic representation from Albenga

The feature of the arch in Fig. 1 confirms the rule of Gautier. Following this hypothesis, the Augustus Bridge collapsed arches could be virtually reconstructed.

#### *3.1.1 Research of geometrical shapes*

A question arises: which is the real arc geometric shape?

The Roman arch is a semicircular one, rarely depressed (O’Connor 1993). Following these considerations two questions arise:

- ✓ Which is the diameter of the standing arch?

- ✓ Is it possible to determine the diameter of the arch that crossed the river Nera, of which only some meters long remains survive on the pier on the left side of the bridge?

These problems are analysed both through the least square analysis of the laser-station surveyed points and through the object recognition method (Cecchi, Passerini, 2003).

In the least square method you assign the representative function of the supposed geometric shape: in the case of the diameter of the arch the circle was the model. According to the least square method, imposing the function fulfilment to each point, you obtain an equations system, where the unknowns are the coefficients of the function itself. With overabundant measures the difference between the experimental laser data and the estimated ones by the approximating function has been calculated and minimized by the least square method.

In the object recognition method, applying the Edge Detector and the Hough Transform processes, first the kind of elementary shape to be recognized inside the digital image (in this case the circle) is established; then the most probable convergence between the objects of the digital image and those supposed is verified.

The obtained results, both through the least square analysis of the laser-station surveyed points and through the object recognition in calibrated digital images, have been analysed and compared (Table 3).

Table 3 : Comparison between the two performed methods

| | Least square method | Edge detector method |
|---|---|---|
| Arch diameter (the arch on left side is approximated to a circle) | 20.05 m | 19.97 m |
| Arch diameter (the collapsed arch is approximated to a circle) | 31.95 m | 32.02 m |

You can note that these values are very similar and the minor differences are essentially due to errors committed in the acquisition and restitution phase, also considering the dimensions, the surveying complexity and the position of the architectural work.

### *3.1.2 The Augustus Bridge virtual reconstruction*

Once established the dimension of the arches and of the piers belonging to the Augustus Bridge, both fronts have been reconstructed and the Augustus Bridge could be virtually reconstructed.

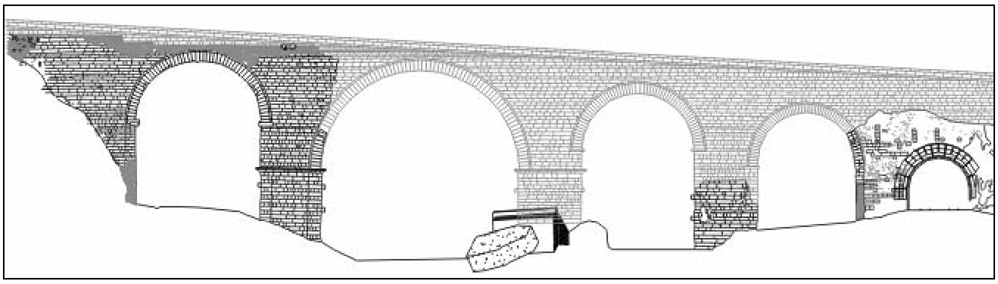

Figure 5 : The front of the virtually reconstructed Augustus Bridge. In black the survey

## 4 FINITE ELEMENT MODELLING OF THE BRIDGE AND HYPOTHESIS ON THE CAUSES OF THE FAILURE OF THE BRIDGE

### *4.1 Finite element modelling*

In Augustus Bridge modelling, the non-linear finite element software ANSYS® has been taken into consideration. This software is able to reproduce the finite displacements, to apply the non-infinitesimal buckling tensor and the non-linear constituent materials employed in the Bridge construction, concrete and travertine (see Paragraph 2.2): in fact these materials show a different behaviour to compression and resistance to tensile stress and present the cracking and crushing phenomenon.

The virtual 3D model of the Augustus Bridge has been meshed with the solid element “Solid 65”, belonging to ANSYS® library, as this element is able to simulate the crushing-cracking processes (Fig. 6).

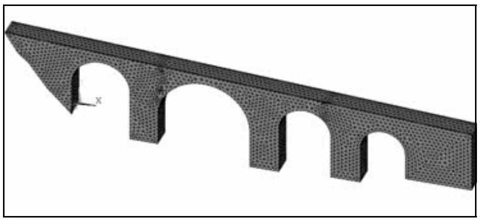

Figure 6 : The 3D model of the Augustus Bridge mesh

### *4.2 First simulation: the collapse of the II and of the III arch*

According to Contratto E. the collapse of the Augustus Bridge in the years 1053-1054 was due to a flood caused by the collapse of the dam built by the Romans probably on the Piediluco lake upstream the “Cascata delle Marmore” (Paragraph 1). But according to many authors (Eroli 1848) (Galliazzo 1995) (O’Connor 1993) the real cause was the slow and progressive subsidence of the second pier, that collapsed definitely in the year 1885 (a photo of it survives Blake 1947). Our research proved that the arch collapsed when the pier subsided 1.50 m.

The showed mechanical model was used to quasi-statically model this subsidence. The model converges up to a maximum subsidence of the second pier of 1.40 m. You can note that the collapse interests the entire second arch, the upper part of the second pier and the third arch. Besides the collapse of these parts of the bridge, there followed immediately the collapse of contiguous regions no longer in equilibrium (Fig. 7).

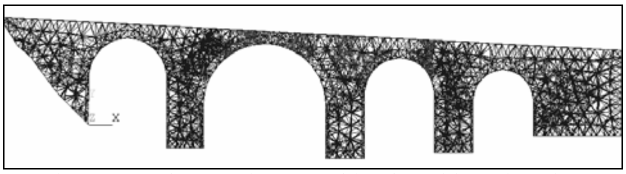

Figure 7 : The graph of crashing/cracking situation

### *4.3 Second simulation: the collapse of the IV arch and the avoided collapse of the first arch.*

The collapse of the second and third arch, caused by the progressive quasi-static subsidence of pier II, produced instability in the surviving parts of the bridge. The collapse and the variation of the volume of the continuum and of its constrains and restrains, triggered a temporary dynamic phenomenon on the first and the fourth arches.

ANSYS®, version 7.0, with the function “Birth and Death” permits such a modelling: so you can cross over a new phase which takes in to account the last results of the first simulation as the initial conditions of the second one.

Out of the results of this second simulation, analyzing the strain graphs, you can note that the fourth arch is much more stressed than the first one (Fig. 8), probably for its much greater stiffness. Then this situation could have caused the collapse of the fourth arch, immediately after the collapse of the second and third arch.

On the first arch, the strains, of minor intensity than those on the fourth arch, would have produced a beginning of collapse, confirmed by the process of vertical translation of the keystone ashlars and by the deep horizontal cracks on three layers, but not the total collapse of the structure.

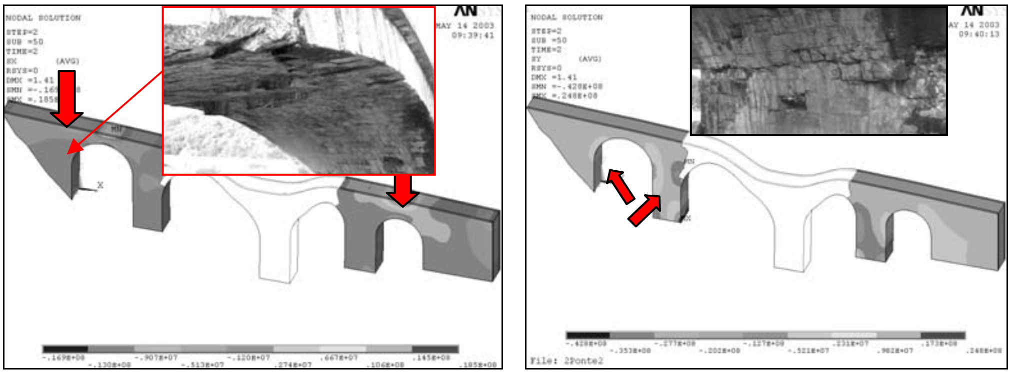

Figure 8 : The strain graph of the remains of the Augustus Bridge. With arrows there have been evidenced the more strained areas.

## 5 CONCLUSIONS

Our deep and long research on the Augustus Bridge shows how different and various disciplines can be well combined together, in order to get a result that surprisingly agrees to today's status of the bridge. In fact, if you have a look to the standing arch, you can recognize what computed out of the simulation: for example the vertical translation of the keystone ashlars and the deep horizontal cracks on three layers.

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