Constructive typologies investigation and approach proposals for the valuation of masonry arch state

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ABSTRACT: A great many among ancient bridges that are still used regularly for the urban mobility, have a lot of problems, caused often by the absence of appropriate maintenance interventions: in fact, an exact valuation of the general “state”, for all the masonry structures and for the ancient masonry arch bridges in particular, is very onerous, also because the existent approach methods are not simply applicable; so, generally, work-assigned people prefer a “total restoration” of the examined structure, even if the real necessity could be lower: sometimes, just these interventions have created the biggest problems. For this reason, it is necessary to determine a no-intrusive approach technique that can be used to know, at every time, the situation of the arch bridges, beyond the entire monumental heritage.

1 INTRODUCTION

Masonry bridges – real structures of civil engineering – represent one of the most important examples of our Country historical-architectural heritage.

The most ancient ones – of Greek-Roman age – have the classic arch-shape allowing to stress the compression ashlars and keeping them together through reciprocal contrast.

Most of those structures have been lasting for centuries until now, thanks also to their great capability – given them mainly by their own weight – of strongly resisting to the stress of movable loads, in opposition to the lighter bridges made up of reinforced concrete and steel.

Many of them are still operating although without any routine maintenance in the course of time.

Other ones, on the contrary, collapsed because of unsuitable interventions both from structural and functional point of view and/or because of demolitions carried out in presence of their hydraulic incompatibility with the present design floods.

Assumed that, this research points out the crucial importance of the intervention criteria consistent with the building conception of those structures since, thanks to the new building materials and advanced technologies of intervention, many of these works have been completely changed in their original structures causing some “gaps”, which made them more vulnerable to external factors.

Indeed, all that shouldn’t be done without a previous careful case-history of the historical period in which they were built and then of the building typologies and technique used.

2 THE ROMAN MASONRY BRIDGES: TYPOLOGIES AND BUILDING TECHNIQUES

Masonry bridges are an important evidence of a past civilisation and ancient building technique.

The bridge – whatever material its made up of: wood, iron, stone, concrete – is an architectural work that has been always deputed to link two places divided by a river, hill, ravine or something else, leaving a space below for water flow or, sometimes, for the eventual traffic or structure discharge (Galliazzo, 1995).

In this way, the bridge has played an important role, during the centuries, not only from the historical-building point of view, but above all for its capability
of connecting Regions, cities and villages making peoples of different civilisation meet together.

In particular, the most ancient ones, the Roman stone bridges, called *pons lapideus* or *pons lapidis*, in order to overcome difficult topographic situations, show a building typology – afterwards become a real reference model – characterised by several arches increasing according to the lights to be covered. They can be symmetric or asymmetric with lateral abutments perforated or not by arches or discharge windows.

Unfortunately, because of the important restorations and changes they have undergone during the ages, the existing Roman bridges often show a shape different from the original one and, contextually, their being different from each other makes a classification difficult to be done.

Generally, classifications are done starting from their usage destination, materials and building techniques used.

Indeed, the most common materials can be found in the several variety of tuff (the tuff of Grotta di Osena, the Fidene tuff and so on), limestone (travertine) and sandstone, as well as iron and lead.

All those materials share a good resistance, easy workability and good adhesion to mortars.

By classifying the bridges with a particular similarity, both as regards materials and building techniques within the Campania Region, we pointed out a peculiar bridge typology, the “Campania type”:

> “Its a particular technique entailing an already built bag core, while the faces consist in bricks (opus testaceum) and/or in opus mixtum ... even if there are tuff block curtains in opus vittatum or in opus vittatum mixtum, also, with a variegated displacement: in general, piers show sight faces or brick faces, or opus mixtum ones with bricks, or very seldom with square worked facing, while the arches are made up of opus testaceum, namely bricks, and often with header arches with double roll and overlapped bipedales” (Galliazzo, 1995).

Among that kind of bridges placed in Campania, we find: viaduct-bridge near the Agnano’s Thermae, viaduct-bridge in Monte Dolce near Pozzuoli, viaduct-bridge in Ronaco near Sessa Aurunca (Coletta, 1989) (Fig. 1).

A special interpretation of the Campania type is represented by the “Trajan type”, that is a typology based not mainly on materials, but on different levels of each pier overlapped layers and on the relation between the header arches of the arcade with the respective crowning frame (Galliazzo, 1995).

The typical example of that type is the Leproso Bridge (Fig. 2) that, dating back to the 1st century B.C., stands on Sabato river – left tributary of Calore Irpino river (Benevento), one of the most important river of South Italy hydrography.
semicircular overhanging buttresses downhill with covers characterised by semi-pyramidal caps with a triangle base and a limestone slabs mat partly repaired.

3 ABOUT THE STATIC CONCEPTION OF ARCH MASONRY STRUCTURES

The problem of safety for arch masonry structures placed in the present historical/monumental building heritage, has become more and more crucial because of the progressive decay of environmental conditions and, sometimes, also arbitrary adaptation and consolidation interventions or, on the contrary, negligent maintenance. Besides, in those areas particularly affected by frequent seismic activity, there is need for preventing the damages produced by a violent and instantaneous earthquake stress, which suddenly transforms the static condition of those particular structures. In those cases, great importance is given to the mitigation of the so-called “seismic risk” and among the factors contributing to its assessment, the institutional competence of architects and engineers is the assessment of “vulnerability”. The work of a structure expert consists in restoring the static functionality of arch bridges by integrally preserving the building logic and the original project, being conformed to the used technologies and materials, in order to obtain the whole structure restoration, without interfering with the layered architectural features of the environmental context.

The consolidation strategies should be chosen in order to ensure structural safety with regard to the staticmechanical (and historical) characteristics and should be conditioned by the destination of use, which binds many structural choices too.

In order to define a methodology on which basing a reliable checking criterion and a suitable intervention procedure, we should know the static behaviour of the masonry building through working out mechanical models targeted to understand, in a satisfying — although not exactly — way, the structure response to external stress.

According to this view, it could be useful to investigate the former routes through a careful research on building methods, as well as the way of conceiving and proportionate the arch bridges used by past designers and builders. Besides, the careful investigation of ruins and collapses, individuation of their causes, comparison among the characteristics of ruined bridges and those well preserved, together with the codifications and rules contained in treatises and handbooks are the elements helping not only to perceive the behaviour but also to point out the structure capacity of bearing external perturbations and therefore its reliability and safety.

All that represents the “experience” heritage of the present-day structural expert undertaking a static restoration of an ancient structure. Indeed, it is the structure itself that gives instructions for its structural recovery to the person understanding its reading code, in the same way as few feeble traces give archaeologists important information about past civilizations.

Masonry resistance to compression and its resistance to traction have always conditioned the stone structures building, in particular the arch ones. The builders — more or less consciously — are engaged in conceiving structures bearing applied loads without provoking traction stresses in order to reach equilibrium by provoking only compression stresses — and of course that should be considered also in static restoring works.

What above said has been confirmed by Heyman’s investigations on ancient monumental buildings and bridges. Indeed, by reviewing the eighteenth-century studies on vault static, he was the first to transfer the philosophy of Limit Analysis to stone structures (J. Heyman, 1966–1969).

Actually, when the hypotheses of elastic calculation fail, the logic to be followed is that of collapse analysis, used for metal structures, according to the hypotheses of non-deformability, no traction resistance and unlimited compression resistance.

In fact from studying old treatises on construction science and reading the ancient structural systems, it comes out how, already in the ancient times, they thought that planning masonry arch structures should be more based on a correct design of arch outline than to the compatibility of applied strengths with material resistance. Therefore the so-called geometric methods” could be the premise for including masonry arch structures into the theory of Limit Analysis theory.

A formulation of the concept of arches cracking mechanism and the relative corollaries on the shape and location of ashlars rotation hinge as consequence of fractures can be already found in Leonardo’s studies.
Although knowing either the basic theorems of Limit Analysis or static cardinal equations, he realized that arch resistance depended on the relations among the sizes of its components.

Only at the beginning of the eighteenth-century, we find the first methods based on assumptions connected with static equilibrium, even if Stevin (1608) and Roberval (1693) had already investigated equilibrium in terms of forces composition principles. It was in 1714, in France, that the first treatise dealing exclusively on bridges was printed, the Traité des ponts, edited several times until 1765. In that treatise, Hubert Gautier collects the principles of correct building, looking for the right relations among abutments, arches and piers but also those related to the easy connection with road network.

Among the hypotheses worked out in the eighteenth-century, the studies of De La Hire (1712), Bélidor (1729) and Couplet (1772) are really interesting. Following the principles of funicular polygon and staticographic methods, they determine the arch outline, seen as a group of ashlar, subject to their own weight, all placed in equilibrium among the adjacent ashlar on which they exert thrusts and receive support and stability. At first, the joints without appeal to friction, afterwards the capacity of resistance to ashlar sliding is looked for in order to overcome equilibrium situations - paradoxical in that context - such as those of the section placed on the bearing base of a circular arch.

However, it was Columb (1773) the studier who, by introducing the concept of friction as basic element in masonry portal-arch equilibrium, finally solved the problem, changing deeply the eighteenth-century mechanic model.

In the nineteenth century, other investigation methods on arch structures stability were worked out and the most important contributions were given by Méry (1833) and Mosely (1840) who, by introducing the principle of “minimum thrust” to be associated to equilibrium, recognized the “hyperstatic” characteristic of the problem and worked out the most widespread method to verify and dimension arch structures until the end of the twentieth century.

In the meantime, with the development of the theory of elasticity and the contributions of Navier (1862), Winkler (1858), Clapeyron (1833), Menabrea (1858) and others, the foundations of the modern Theory of Structures were laid.

In those studies we get a clear view of the question concerning structures resistance both from the static and strain question, because they point out the need for checking that in all the building elements the stress state and strain one are included in the materials levels of admissibility.

That represents an important turning point: the attention of building experts is no more paid only to the “design” but also - and above all - to “verification”.

On summing up, in the eighteenth-century treatises, arch is seen as a system of rigid ashlars with an indefinitely compression resistance (rigid model). They pointed out the pressure lines, all meeting equilibrium requirements, but weren’t able to univocally determine the “real” pressure line since, starting only from static, it was no possible to individuate the value of the keystone thrust as well as its exact application point.

All this static uncertainty comes from the fact that such attempts aimed at finding a solution to the hyperstatic problem with equilibrium as the only requisite, not recognizing the other basic aspect of the Structures Theory, i.e. the congruence of strains.

With the Theory of Elasticity development, arch was studied as an elastic beam with curvilinear axis fixed or hinged at the ends and so being hyperstatic and no more as non-deformable rigid solid.

At present the static of masonry arch structures can be investigated through the elastic analysis, or through the Limit Analysis. The elastic calculation can be used in the hypothesis of a structure perfect integrity and, therefore, dealing with masonry structures, only when there are compression stresses or a few traction. So it cannot be used in case of damage – the most frequent case in interventions of restoration and consolidation.

By referring to a collapse situation, the Limit Analysis gives valid indications on structures safety levels, but it doesn’t contribute to understand the intermediate states through which the examined structure has shown or is showing the first pathologic signs (Baratta, Voelillo 1986).

Therefore, starting from those assumptions, we resorted again to more sophisticated calculation techniques, which take more into account the composition of masonry material being more suitable to the real behaviour of masonry structures and allow to investigate the fracture phase – being intermediate between elastic behaviour and collapse.

4 PRINCIPAL MASONRY BRIDGE PROBLEMS

The worst possible damage that a masonry bridge can undergo during its existence, is due to ground subsiding, caused by sudden alterations of the basement geology, or to the arising of horizontal loads caused principally by earthquakes; effects as dangerous can be provoked also by persistent and frequent vibrations, i.e. those provoked by trains crossing or by intense car traffic.

A masonry bridge, such as can be frequently found in Italy, often designed a lot of time before the seismic normative entry, and with resistance criteria valid only for vertical loads, resists the horizontal loads practically only thanks to the impressive mass that, through the inertial force action, tends to bring back
the structure into the initial configuration, contrasting the ground acceleration.

The expression of the inertial forces is, in fact

\[
F_{ix}(x,t) = -\mu \dot{u}_i(x,t) + \ddot{u}_{gr}(t);
F_{iy}(x,t) = -\mu \dot{u}_j(x,t) + \ddot{u}_{gr}(t);
\]

where

\[
\mu = \frac{\gamma_m \cdot A_i}{g}
\]

is the linear unity mass density;

\[
\ddot{u}_i(t) e \ddot{u}_{gr}(t)
\]
is the ground acceleration, respectively horizontal and vertical, \(\gamma_m\) is the material specific weight, \(A_i\) is the transversal section area of a generic ashlar arch, and \(g\) is the acceleration gravity. So the inertial forces depend on the ground acceleration, on the structure mass and on the material specific weight that, in the masonry case, has a principal role for the resistance of the whole structure.

In the first years of the XVIII century, the bridges structural design were brought about by means of empiric formulations, i.e. as the Croizette-Desnoyers formula (Baratta, 1988) that reads

\[
s = a + b\sqrt{2R}
\]

where \(s\) is the arch key thickness, \(R\) is the radius of the circle concerning the impost and \(a\) and \(b\) are two coefficients that change, respectively, the first in the case of an ordinary street or a railway one, and the second in accordance with the form.

The thickness \(s\) was multiplied by a coefficient depending on the overstructure thickness, on the overload value and on the stone break resistance; this one is the only parameter considering the material used for the bridge construction. The bridge arches are generally realized with stones, bricks or freestone; in a lot of cases, the parts considered of "secondary importance" were filled up with nogging. Also the "shoulders" were calculated with approximated formulas, i.e. the one used by the Genio Civile Italiano, that is valid for the circular arches

\[
S = 0.5xh + 0.4xL + 2x(10 + L)xL/(100xf)
\]

where \(h\) is the impost share, \(L\) is the arch span and \(f\) is the arrow.

In the case that the resultant thickness needs to be reduced, an artifice could be used consisting in the perforation of the lateral walls, so that the light can be subdivided in a lot of arches, characterizing, with this structural scheme, the whole bridge architectural aspect (Fig. 5). Generalizing under the term "masonry" all the materials that have an optimal traction resistance and a next to null pressure resistance, that have a "fragile" failure and can have either an isotropous behaviour (nogging) or an anisotropus one (squared block masonry), it is possible to say that, if a material with these parameters has certainly a good behaviour under vertical forces, it is not so good for structures subjected to horizontal forces, especially dynamics, that require the material to have a strong amount of ductility. In a special way, the ashlar masonry arch, whose resistance is given principally by the friction that the stones exercise between each other, collapses when a mechanism activated, i.e. by a seismic forcing, makes vain the "reciprocal contrast" action between the ashlars and makes impossible the return to the quiet configuration, which the inertial forces could instead favour in case the arch were kept solid (Fig. 6).

At present, in order to avoid these events, only two real ways exist: the "traditional" insertion of chains and tie rods that make the ashlar arch solid and maintain it anchored to the lateral walls and to the other structural elements, in the attempt to effect an improbable
aseismic equalization, or the whole “investigation” of the structure, grasping the history (the original project, the possible alterations, the brekages and strengthening intervention subjected in the last years, etc.) with the aim to “prepare” it for the event, to quote Giuffrè “se conosciamo il “cosa”, ne scaturisce il “come”», meaning as “come” the executed intervenst in an aimed way. In this background, the seismic vulnerability and the necessity of damage valuation must be considered, as well as the so-called “attempt damage”, whose knowledge could allow the limitation of negative effects on the structure.

4.1 The earthquakes question and the seismic vulnerability

Since it is difficult that these bridges, – built up, as can be seen, with structural concepts very far from the ones used at present – are equalized to the seismic laws, the only possibility to defend the historical bridges from the seismic effects (main and feared cause of monuments destruction in Italy), is to try to anticipate the impact in any way, whether it be “material” (on the structures) or “moral” (on people). In other words, the “attempt damage”, that is the problem to determine a-posteriori the risk level in order to prevent the damage. The seismic risk is treated in the probabilistic way through the old earthquakes catalogation that have occurred in a specific area, with the aim to define the place tendency to be an earthquake centre; some electronic programs, carried out by researches in the field, can localize, on the basis of probabilistic calculations given by the past earthquake catalogation, what is the probability that a seismic event will occur again in that specific site, what its intensity will be, and even when it will approximately occur. On the basis of these programs, that can be inserted in the “seismic risk” field, the structural damage can be defined; such a matter, concerns the field of civil engineering, together with the problem of structural vulnerability. As it was said, the structural vulnerability of any construction, in the specific case of a bridge built before the seismic law, refers to define the attempt damage in the earthquake shock case; so the vulnerability is linked to the seismic risk and to the earthquake foresight just in this sense. The probability matrix of damage, probabilistic expression of seismic vulnerability, is built defining a vector that contains the various levels of damage $D_i$, included between 0 (unbroken system) and 1 (collapsing system); the seismic intensity vector is also defined, containing the different levels $I_k$, that are described through deterministic parameters (i.e. as the ground acceleration peak). So the vector $I$ represents the seismic intensity medium value for a given event recorded within a specific area. In order to obtain the local value $H$, it is necessary to introduce the probability $P(I_k)$ that in a given time space, a medium intensity earthquake may occur. In this sense, the local value is expressed by the relation

$$P(H) = \sum_i P\left(\frac{H}{I_k}\right) P(I_k)$$

Finally, the probability that a damage level $D_i$ is achieved, can be expressed by the relation

$$P(D_i) = \sum_j P\left(\frac{D_i}{H_j}\right) P(I_j)$$

The term $P(D_i/H_j)$ represent the elements of damage probability matrix, which expresses the seismic vulnerability in the probabilistic sense. In deterministic sense, diagramming the local seismic intensity and the damage level, the vulnerability curve is obtained (Fig. 7).

If a bridge shows an anti-symmetric plan and so some different structural characteristics and a behaviour variable with the action direction, the response of the structure or of the single resistant element can be influenced by the direction before than by the intensity of the forcing function. The response modality, as well as the element characteristics, lead to the individuation of a probable break mechanism, whose activation is subjected to the action explosion, to its intensity and to its duration.

The break mechanism involves the damage of a structural element, which occurs in the masonry arch when the material cracks itself and in that point a lateral hinge is actived; the relative rotation between the ashlars is so allowed. The hinges set, forms a so called “collapse mechanism”; in accordance with it, the arch can fall because of equilibrium loss (in particular, refering to Figure 5, the hinges are aligned) and its activation depends on motion intensity and duration.

The causes that contribute to the activation of the collapse mechanism are various: there is also the fact that the element is isolated – as in the case of bridges – the place conditions (ground subsiding etc.), the material degrade and its mechanical characteristics. At last,
a mechanism activation doesn't necessarily imply the structural collapse, which, as already said, is very subjected to the motion duration.

From analytic view, the structural damage is related to the system plastic field excursion, and it is in connection to measures as deformations, displacements etc.; in the masonry case, the system can be schematized with a rigid-failure structural model; this model, as already said, arrives to the collapse for lost equilibrium (Fig. 8).

For this reason, for the attempt damage valuation, it is necessary to consider the action intensity and duration, both factors that determine the damage entity and the stress level in the material. So the vulnerability is estimated as the sum of two effects: the first doesn't depend on the ground acceleration characteristics, but i.e. by the material used for the construction or by the damage state and the second depends on the construction geometry or on its boundary conditions.

Other methods to determine the vulnerability curve are based on the constructions filing from experts, who fix belonging classes, according to the material used (i.e. masonry of lateral walls, of verticals etc.), with the structural state or with other parameters that are fixed on place and time by time judged suitable; on the basis of these comparisons and of one's own experience, they assign a vulnerability index that doesn't consider at all the above said boundary conditions.

The choice of the methodology to be used to define the vulnerability index and to give a given bridge a "supportability index" for a more or less serious event, and also to define the vulnerability curve and the damage probability matrix, depends on the construction age; this generally indicates whether the bridge is built up with aseismic criteria, or not: in fact it is necessary to consider that the post-law built up structures or those that have had aseismic equalizing works, can appear sufficient a qualitative investigation (vulnerability class belonging), while for the ante-law built up structures, it is necessary to use appropriate methods, based on Mercalli and MSK scales. These scales, afterwards shortly illustrated as an example, must be equalized for the examined constructions, carrying out the single notices for the specific structures exploration, as the masonry bridges that are investigated in this work.

5 THE INTERVENTION POSSIBILITIES

5.1 The seismic intensity scales

The seismic intensity scale MSK (Medvedev, Sponhuer, Karnik, 1968), which subdivides the masonry construction according to the portant parts materials, is founded on three basic parts:

(1) Three classes are considered, arranged in estimated way for growing seismic vulnerability (i.e. A, B, C).
(2) Six damage levels are considered for every class, between "0" (no damage) and "5" (total collapse).
(3) For every damage class a quantification is associated which, in the MSK formulation, refers to the construction percentage to which is possible to ascribe a given damage level.

The seismic intensity is ascribed on the basis of quantifications (3) found for each combination obtained crossing (1) and (2), for the intensity between V and X.

The tables obtained arranging the seismic degree in abscissas and the damage levels in ordinates for every typological class, can be used to estimate either the structure per cent that undergo a determined damage level for a determined seismic intensity or to value an earthquake intensity on the basis of the damage pointed out. The other valuation method used at present is based on the assumption of the Mercalli's scale; which is suitable to the same double aim, but which is also functional to direct observation (i.e. to value the bridge per cent that undergo a determined damage level for a determined seismic intensity, it is necessary to know this one and that is calculated with analytical methodologies; vice versa, to value the seismic intensity on the base of the pointed out damage, it is necessary to establish the damage amount). In the follow, two phases of Mercalli's scale.

(1) Damage prevision (for seismic intensity between VIII–X and attempt damage description for every intensity).
(2) Intervention strategy for every seismic intensity (i.e. ≤VIII ⇒ nothing intervention).

5.2 The techniques for masonry arches

The typological analysis allows to locate the constructive phases succession and these reveal the vulnerable belts. This way is obviously useful to the attempt damage preventive evaluation and to locate the restoration techniques that spring from the natural evolution
of the constructive formality that must be analyzed. In the latter, the Mercalli and MSK scales define a vulnerability empirical evaluation, analyzing time by time the structural elements. But these scales, formulated essentially for historical centres, must be reported to bridges problem and the single structural elements must be pointing out in precision way, thinking, over the other things, that structure isolated by the urban contest, if it is more vulnerable because it cannot rely on the aggregate capacity to be solid, on the other hand is more assimilated to a structural model, and it easily reports itself to a determined static scheme. Referring to the picture (Fig. 9), the most important structural parts of the arch bridge are pointed out: the arch 1 is the street support, the props 2 strengthen the lateral parts of the arch; the “shell” 3 attend to protect the arch masonry against water infiltrations; the headwalls 4 raise themselves from the arch extremities to the completion floor, interpose with a earth or gravel refilling, in order to reach the road level; the shoulders 5 sustain the arches and enter deeply into the ground with the foundations.

6 CONCLUSIONS

Well constructed masonry bridges – specially the realised with high quality materials and suitable building techniques ones – keep almost for ever.

Unfortunately, by reason of the important restorations and changes they have undergone during the ages, the existing Roman bridges often show a shape different from the original one and, contextually, a classification of the various typologies, became too complex and inaccurate to do.

In order to assure security and preservation, great restorations should be avoid; on the contrary, several routine and regular maintenance interventions in the course of time should be effected, to the aim to assure the old structure preservation, and at the same time, the “maximum duration” through the “minimum intervention”. A diligent classification of all bridges and viaducts in Italy, and a valuation of the attempt damage through the MSK and Mercalli scales – if it is possible – through probabilistic methods – in alternative – could suggest accurate interventions able to warrant the two most important requirement that the historical heritage needs: safety and functionality.

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