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VALUATION OF SEISMIC VULNERABILITY AS SUPPORT FOR CONSERVATION OF MASONRY BRIDGES

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Abstract. *The main problems connected with the masonry bridges typology are various and complex, from the ageing of materials, to the variation of exercise loads, the degradation of the structural scheme caused by natural events, such as the earthquakes; last, but not least, there is the recent site seismic classification that requires a new determination of the existing safety coefficient of the structures. Most structures of this kind are normally used even in our days, even if they have undergone no appropriate maintenance interventions, while, sometimes, the very equalization interventions, unsuited on the structural or functional level, have created the biggest problems, causing the final deterioration of the structures and the consequently demolition sentence (or, even worse, their sudden collapse). Several routine and regular maintenance interventions, pointed out by the "seismic vulnerability" techniques through the attempt damage definition, could be avoid great damnages and subsequent great restorations.*

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 it's 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*"[1].

So doing, 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.

[1] V. Galliazzo, *I ponti Romani,* Canova 1995, pg. 153

Generally speaking, 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"*[2].

Figure 1. Ronaco viaduct-bridge in Sessa Aurunca.

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 (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*"[3].
The typical example of that type is the Leproso Bridge that, dating back to the 1st century B. Ch., stands on Sabato river - left tributary of Calore Irpino river (Benevento), one of the most important river of South Italy hydrography.
It has a typical Roman hog-backed structure, with quite short abutments despite its remarkably length (Fig. 2).

[2] V. Galliazzo, *I ponti Romani*, Canova 1995, pg. 555-556

[3] V. Galliazzo, *I ponti Romani*, Canova 1995, pg. 556

Figure 2. An old picture of Leproso bridge.

It consists of three – once five - arches (with discharge and flow windows), realised to repair the damages caused by the 1702 earthquake (Fig. 3).

Figure 3. Comparison with a present picture shown Leporoso bridge

Although it has been restructured many times, it still preserves some original elements such as: the semicircular overhanging buttresses downhill with covers characterised by semi-pyramidal caps with a triangle base and a limestone slabs mat partly repaired. **(S.D.)**

2.1 The maintenance of Roman bridges as basic premise for their preservation

Well constructed masonry bridges - specifically realised with high quality materials and suitable building techniques - last almost for ever.
Despite that, at present there are several causes that make them collapse. The most recurrent are the following:

- construction defects, depending on the quality of materials and their installation;

- foundations saps because of water, caused both by their bad construction and mistakes in calculating permanent and live loads;
- structure deterioration caused by lack of maintenance;
- human action that –intentionally or not – damaged the old building typology through unsuitable consolidation interventions;
- the increasing stresses usually caused by the change of their original usage destinations.

Two are the intervention typologies in use until the beginning of the 20th century:

1) restoring the bridge by considering its historical evidence, namely preserving it. It follows that the interventions are carried out using the collapsed material or new material but similar to the old one;
2) rebuilding the bridge with partially or completely new material, creating a new structure.

Among the most important restorations carried out in the South of Italy we find the Devil Bridge at Faicchio and the Tufaro bridge at Montesarchio.
In order to avoid important and expensive repairs, "minimum and targeted interventions can be "planned", regularly marked, through which assuring the bridge efficiency, but above all contrasting the slow deterioration caused by the course of time. Routine maintenance represents – therefore- the basic premise in order to increase the "useful life" and preserve the historical heritage, avoiding the troubles caused by great projects of extraordinary maintenance.

Figure 4. Diavolo bridge.

That is the reason why the intervention should be estimated starting from the very moment of structure – planned ex novo - begins operating.
In the course of time, the structure should be constantly monitored in order to previously point out the beginning of any process of decay, which makes the structure vulnerable mainly in relation to natural events (floods, rain, wind, earthquake).
"The never-ending life seems, therefore, to be a principal characteristic intentionally "researched" by many roman bridges and that is the ideal hope to many similar stone structures still existing, sometimes unbroken, in the different regions under Roman dominion

in the past and whose life, although affected by time and men, lets the experts astonished still today"[4]. **(S.D.)**

3 PRINCIPAL MASONRY BRIDGE PROBLEMS

The worst possibile 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 arch bridge, such as can be frequently found in Italy, often designed a lot of time before the seismic normative entry, and with resistence 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. 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[2], that reads

$$s = a + b\sqrt{2R} \tag{1}$$

where s is the arch key thickness, R is the radius of the circle concerning the imposts 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 resistence; this one is the only parameter considering the material used for the bridge costruction. 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

$$S = .05xh + .40xL + 2x(10 + L)xL/(100xf) \tag{2}$$

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.

Generalizing under the term "masonry" all the materials that have an optimal traction resistance and a next to null pressure resistence, that have a "fragile" failure and can have either an isotropous behaviour (nogging) or an anisotropus one (squared block masonry), it is possibile 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 duttility. In a special way, the ashlar masonry arch, whose resistence is given principally by the friction that the stones exercise between each other, collapses when a mechanism activated, i. e. by a seismic forcing,

[4] V. Galliazzo, *I ponti Romani,* Canova 1995, pg. 260.

makes vain the “reciprocal contrast” action between the ashlars and makes impossible the retun to the quiet configuration, which the inertial forces could instead favour in case the arch were kept solid. 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 a-seismic 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[3] <<se conosciamo il “cosa”, ne scaturisce il “come”>>, meaning as “come” the executed intervents in an aimed way. In this background, the seismic vulnerability and the necessity of damage valutation must be considered, as well as the so-called “attempt damage”, whose knowledge could allow the limitation of negative effects on the structure.

3.1 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, wheater 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 oder to prevent the damnage. The seismic risk is treated in the probabilistic way trought 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 elettronic 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 costruction, 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 damnage D_i included between 0 (unbreaked system) and 1 (collapsing system); the seismic intensity vector is also defined, containing the different levels I_k, that are described trought deterministic parameters (i.e. as the gound acceleration peack). 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_j 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

$$P(H_j) = \sum_k P\left(\frac{H_j}{I_k}\right) P(I_k) \tag{3}$$

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

$$P(D_i) = \sum_j P\left(\frac{D_i}{H_j}\right) P(I_k) \tag{4}$$

The terms $P\left(\frac{D_i}{H_j}\right)$ represent the elements of damage probability matrix, which expresses the seismic vulnerability in the probabilistic sense. In deterministic sense, diagramming the local seismic intensity H_j and the damage level D_i, the vulnerability curve is obtained.

If a bridge shows an antisimmetric 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 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 damnge 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 losting equilibrium (Fig. 5). For this reason, for the attempt damnage valutation, 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 costruction 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 "sopportability index" for a more or less serious event, and also to define the vulnerability curve and the damnage probabilità matrix, depends on the construction age; this generally indicates whether the bridge is built up with a-seismic criteria, or not: in fact it is

necessary to consider that the post-law built up structures or those that have had a-seismic 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 examinated costructions, carrying out the single notices for the specific structures exploration, as the masonry bridges that are investigated in this work.

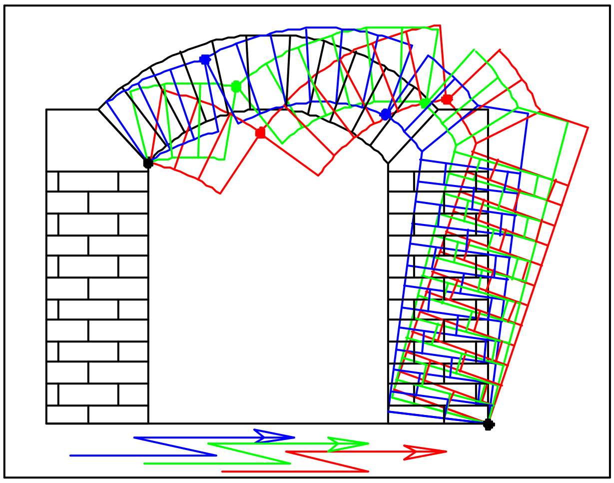

Figure 5. The arch model during the motion.

4 THE INTERVENTION POSSIBILITIES

4.1 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 possibile 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 damnage levels in ordinates for every typological class, can be used to estimate either the structure per cent that undergo a determined damnage level for a determined seismic intensity or to value an eartquake intensity on the basis of the damnage pointed out. The other valutation 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 knowthis one and that is calculated with analytical methodologies; vice versa, to value the seismic intensity on the base of the pointed out damnage, it it is necessary to estabilish the damnage amount). In the follow, two phases of Mercalli’s scale

1. Damnage prevision (for seismic intensity between VIII-X and attempt damnage description for every intensity)
2. Intevention strategy for every seismic intensity (i.e. <VIII $\Rightarrow$ nothing intervention)

5 CONCLUSIONS

Well constructed masonry bridges - specifically realised with high quality materials and suitable building techniques - last almost for ever. 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. In order to assure security, on the one hand, and preservation on the other hand, we should avoid great restorations and, of course, organise several routine and regular maintenance interventions in the course of time, aimed mainly at assuring the old structure preservation by increasing, at the same time, the “useful life” through the “least intervention”. A diligent classification of all bridges and viaducts in Italy, and a valuation of the attempt damage throug 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.

REFERENCES

[1] F. Jorini, *Teoria e Pratica della Costruzione dei Ponti in legno, in ferro, in muratura*, Hoepli, Milano, (1927).

[2] Baratta, A. *La protezione antisismica dei beni architettonici: problematica e considerazioni di metodo*. Istituto di Costruzioni Facoltà di Architettura Napoli (1988).

[3] Giuffrè, A. *Sicurezza e conservazione dei centri storici*. Editori Laterza, Roma (1993).

[4] S. D'Agostino, *"Vulnerabilità del patrimonio costruito, prevenzione e conservazione"*, Acta Neapolitana, Ed. Guida (1994).

[5] V. Galliazzo, *I Ponti Romani*, Canova, Treviso, Vol. I, II (1995).

[6] P. Roca, C. Molins, J. L. Gonzalez, A. Casals, *Analysis of two medieval stone masonry bridges*, Architectural Studies, Material & Analysis - Structural Studies of Historical Buildings IV, Vol I, STREMA, Creta, (1995).

[7] Baratta, A. Colletta, T. Zuccaro, G. *Seismic risk of historic centre*. La città del sole, Napoli (1996).

[8] C. Torre, *Ponti in muratura*, ALINEA, Firenze, (2003).

[9] Resemini, S. Lagomarsino, S. *Sulla vulnerabilità sismica dei ponti in muratura*, XI Congresso Nazionale L’Ingegneria Sismica in Italia, Genova (2004).