Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 2423-2430

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

NON LINEAR STATIC AND DYNAMIC ANALYSES OF THE AUGUSTUS BRIDGE IN NARNI, ITALY: AN INSIGHT INTO THE MECHANICAL PROPERTIES OF ROMAN CONCRETE

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Keywords: Masonry arch Roman bridges, Roman concrete, Earthquake, Non-linear static analysis (pushover), Non-linear dynamic analysis.

Abstract. *The present paper is devoted to the discussion of the results obtained by a series of non-linear static and dynamic analyses performed on a relevant structural Roman artwork: the Augustus bridge in Narni (Central Italy). The Roman bridge, which was in origin arranged into four arches with a maximum span of approximately 32 m, is nowadays constituted by the lateral left arch and a portion of the right part of the abutment. As a matter of fact, it ruined some centuries ago because of a combination of different causes. A recent experimental investigation pointed out the role played by a vertical foundation settlement mechanism that took place at the base of the second pier and probably led to the collapse of the two central arches. In addition, the highly prone seismic area and the great variability of the mechanical properties of the Roman concrete used to construct the bridge clearly played a crucial role. The present work is aimed at investigating the influence of such parameters on the collapse of the original structure. To this scope, a 3D model has been created starting from the geometric survey of the original four arched bridge. The double leaf masonry used by Romans has been considered in the present analyses subdividing the adopted discretization into two materials: the Travertine stone adopted for the outer leaf and the Roman concrete used as filling. Two series of non-linear static and dynamic analyses are performed respectively applying: (i) a G1 distribution of the horizontal loads along the height of the bridge and (ii) a spectrum-compatible accelerogram with two components along the vertical and transversal directions. The results are comparatively assessed with respect to the experimental observations of the ruins of the Augustus bridge. Particular attention is focused on the global force-displacement capacity curve and the damage maps obtained at the end of the analyses. The numerical results, in addition to the experimental observations, clarified the strong negative effect that a vertical settlement of the ground had on the stability of the bridge.*

Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5578.17286

1 INTRODUCTION

Roman bridges were an essential part of the road system of ancient Rome, which at the time of Diocletian reached a length of about 53000 miles, giving rise to several road systems of many modern nations around the Mediterranean Sea. As a matter of fact, Romans developed a particular technique to build their bridges, especially piers and abutments, i.e. external masonry coats made by large stones filled with pozzolanic concrete. Such building technology gave rise to extremely resistant structures, which still survive. The construction of bridges and viaducts grew and extended gradually to the entire Roman Empire during the first century BC. With the rise of Augustus and the consequent beginning of the Imperial Age, there has been throughout the Empire, an energetic restoration of numerous road layouts with the resulting construction or rebuilding of many bridges. From the late Republican bridge, meant as civil structure of crossing, in the Augustan age the bridge started to be considered as a monument, tangible expression of unity and power.

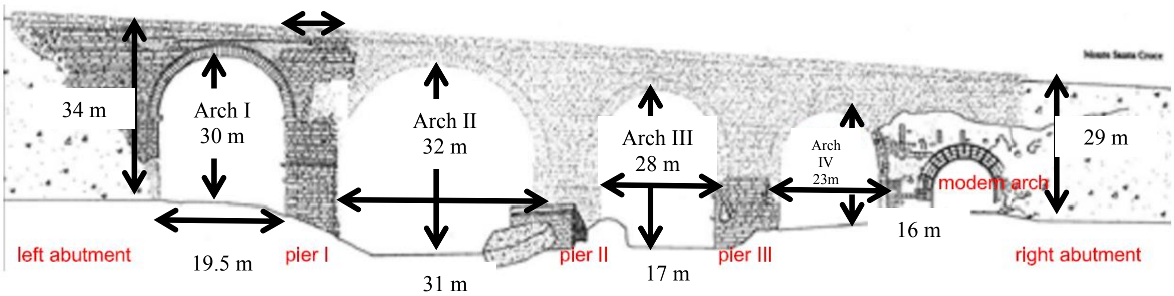


Figure 1: Hypothetical configuration of the Augustus Bridge in Narni (picture taken from [1]).

The present paper is intended to analyze the seismic behavior of one of the most relevant Roman artwork: the Augustus bridge. The existing parts of the structure are depicted in Figure 1 in a darker color, whereas the hypothetical reconstruction of the original bridge is clearer. As can be noticed, only a portion of the bridge is nowadays still visible, indeed it ruined some centuries ago due to a combination of different causes, which have been investigated in the present work. As confirm by recent experimental campaigns, probably a vertical foundation settlement mechanism took place at the base of the second pier, leading to the collapse of the two central arches. In addition, the highly prone seismic area and the great variability of the mechanical properties of the Roman concrete used to construct the bridge clearly played a crucial role. To understand the influence of such parameters into the failure of the original construction, a wide numerical investigation has been conducted by the authors. For the sake of brevity, in the present paper only the most relevant results have been presented and critically discussed.

2 AUGUSTUS BRIDGE IN NARNI

The Augustus Bridge is located near Narni, an Umbrian town in the Central Italy [1][2]. It was probably built in 27 BC, in occasion of a restoration of the Via Flaminia, motivated by military reasons. Probably the bridge was already partially collapsed in the seventh century and it has been rebuilt reusing the materials recovered from the collapse and following the example of the previous design. Later, in 1053 or 1054 AD, according to many scholars, it seems that an overflow of the river (caused by the collapse of a dam upstream) definitely brought down the superstructure of the bridge that was not rebuilt anymore. It happened probably because the knowledge and the techniques of that period did not allow a reconstruction in the original configuration, and so the function of crossing the valley was taken from the medieval bridge built a little further upstream, whose piers were made mostly with salvaged materials coming from the collapse of the Augustus Bridge of XI century. In the nineteenth century, there was a real working plan of restoration of Augustus Bridge, after the collapse of medieval bridge, in 1819 AD. But the situation changed only in 1885 AD, when a flood of the river Nera overthrew the second pier from left, reducing it into pieces. The geometrical configuration of the Augustus bridge, which was in origin arranged into four arches with a maximum span of approximately 32 m, is showed in Figure 1. The numeration of piers and arches is done in ascending order from left to right (or from South to North). Considerably interesting, from the structural point of view, are the existing geometrical and mechanical insights [1], concerning the concrete infill and the travertine coating. In [1], basing on analyses and studies conducted on the bridge, the authors trace the causes of the collapse to a progressive foundation settlement of pier II. As a matter of fact, on the basis of geometrical surveys and historical constructive considerations, it is believed that the original configuration was the one with 4 arches with springers of circular arch II at the same height. The lowering of about 2.9 meters of the dosseret block of pier II, according to [1], is due to the foundation settlement of the pier itself occurred during two thousand years.

3 NUMERICAL ANALYSES

Two series of non-linear static and dynamic analyses have been performed on both the entire structure and the still standing part of the Augustus bridge. From a structural point of view, such Roman artwork has been built adopting a peculiar construction technique, known as “Opus quadratum”. It consists of dry stones with regular parallelepiped ashlars positioned mostly in horizontal rows (Figure 2-a). As clearly visible in Figure 2-a, arches, piers and abutments of the Augustus bridge have been constructed using the aforementioned technique. As a matter of fact, masonry blocks of travertine have been arranged in an outer coating, whereas the infill is in Roman concrete [1][3][4][5].

-a

-b

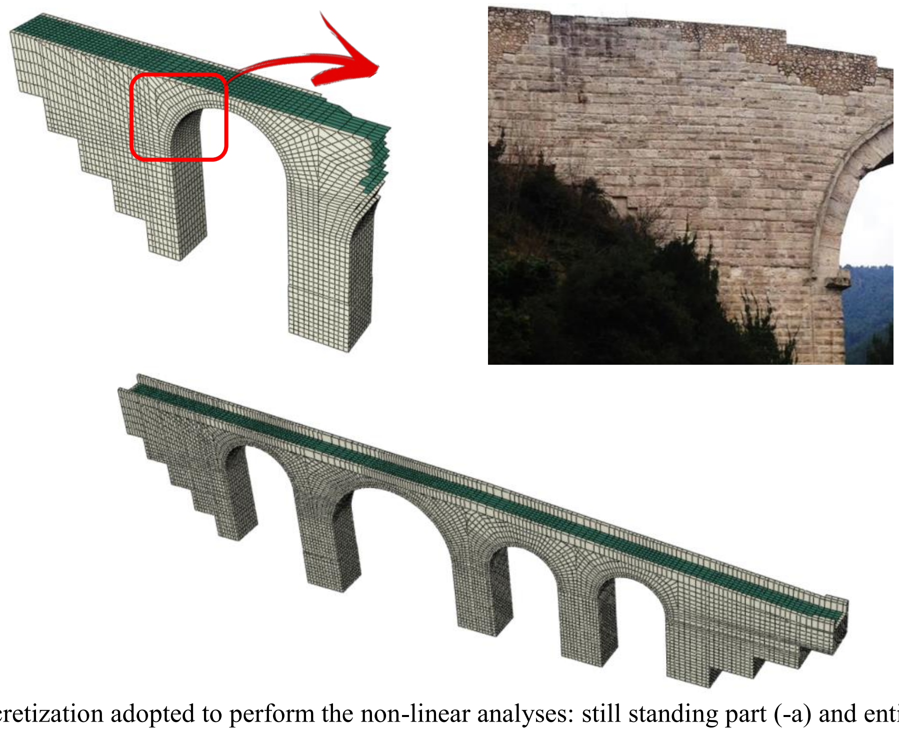
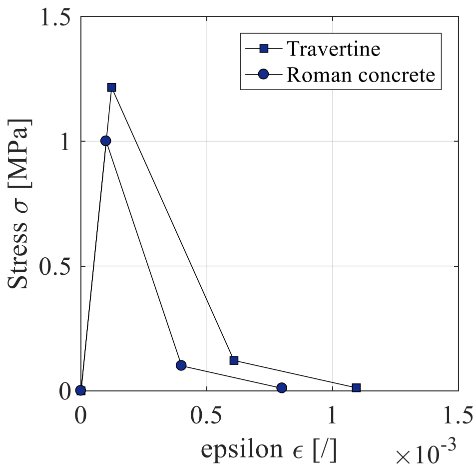


Figure 2: Discretization adopted to perform the non-linear analyses: still standing part (-a) and entire structure (-b).

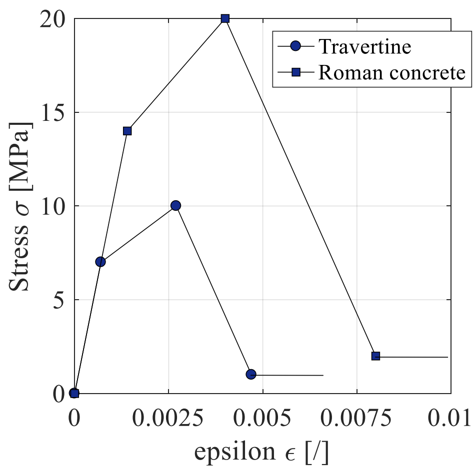
In order to understand the role played by the concrete infill into the structural behavior of the Augustus bridge, the authors decided to separately model the outer layer of the travertine and the Roman concrete. To this scope, a refined discretization has been employed to perform the analyses. The meshes, which are depicted in Figure 2 are composed by 12480 and 38136 FEs, respectively for the two considered models. The elastic mechanical properties of the constituent materials are summarized in Table 1. It is worth mentioning that such parameters have been preliminarily validated through a series of numerical-experimental comparisons based on the results obtained by some dynamic investigations. The inelastic stress-strain curves employed within the FE software Abaqus [6] are depicted in Figure 3 for all the materials involved into the simulations. In particular, the authors decided to adopt a Concrete Damage Plasticity model, which is already available into the adopted FE software, to describe the tensile and compressive behaviors of both travertine and Roman concrete. As a matter of fact, brittle materials frequently exhibit a poor behavior in tension and are particularly prone to experience severe damages when subjected to alternate tensile-compressive actions like those produced by a seismic event. From a numerical point of view, the CDP model allows to consider both tensile cracking and compressive crushing failure mechanisms, as well as the progressive degradation of the stiffness as a result of damage phenomena. It is opinion of the authors that such model is particularly suited to study the damaging processes caused by dynamic excitations.

	Young Modulus [MPa]	**Poisson's ratio [-]**	**Specific weight [kg/m^3]**
Travertine	10000	0.1	2200
Roman concrete	10000	0.1	2250

Table 1 Mechanical properties adopted for the constituent materials, according to Cecchi (2003).



-a



-b

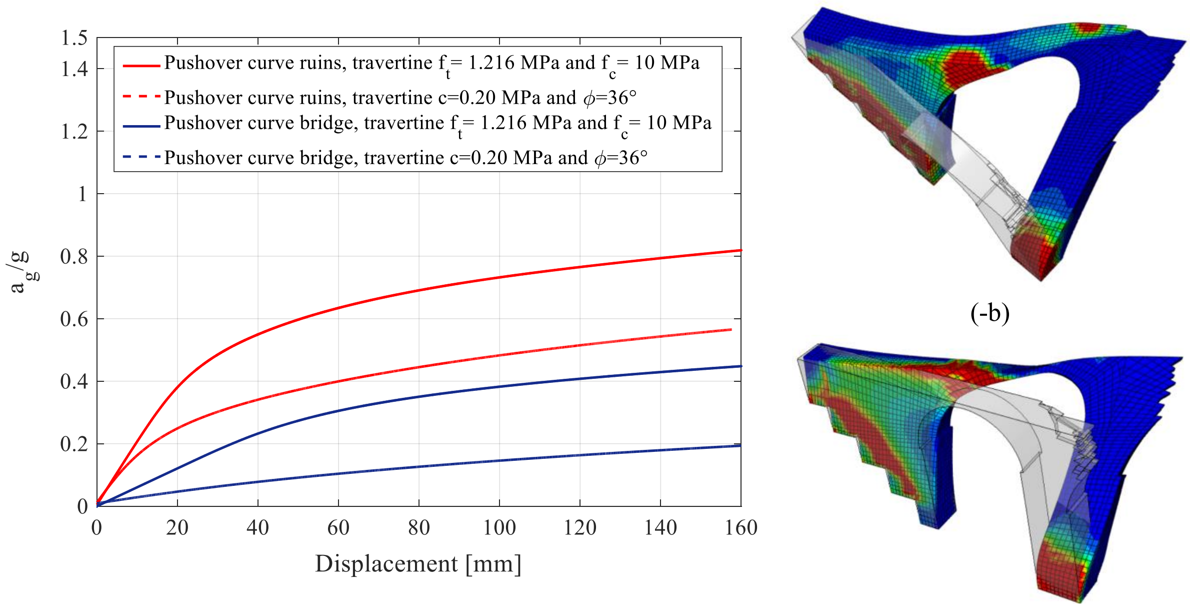
Figure 3: Uniaxial stress-strain behaviors adopted for Roman concrete and travertine in tension (-a) and in compression (-b).

4 NUMERICAL RESULTS

In the present section, the results obtained by a series of non-linear static and dynamic analyses are presented and critically discussed.

4.1 Pushover analyses

A series of non-linear static (pushover) analyses have been conducted on the Augustus bridge adopting both the discretizations showed in Figure 2. The simulations have been carried out according to the Italian code, which suggests adopting two different distributions of the horizontal forces along the height of the structure. For the sake of brevity only the analyses performed assuming a G1 distribution of the horizontal loads (reverse triangular) are herein discussed. In order to study the structural response of the bridge when subjected to a seismic event, the mechanical properties of the constituent materials have been varied. As a matter of fact, the following inelastic parameters have been adopted for the Roman concrete: f_t=1.0 MPa and f_c=20 MPa and c=0.17 MPa and φ=36°. The peak strengths assumed for the travertine are scaled accordingly, so that f_t=1.216 MPa and f_c=10 MPa in the first case and c=0.20 MPa with φ=36° in the second. It is worth mentioning that, in the second series of analyses, poor mechanical properties have been assumed for both the constituent materials, simply because such parameters are similar to those used by the Italian code to represent a common masonry material. The comparison between the results obtained at the end of the pushover analyses is depicted in Figure 4-a. The curves have been obtained monitoring the horizontal displacements of a control point located in the keystone of the first and second arches, respectively for the still standing part and the whole bridge.



(-b)

(-a) (-c)

Figure 4: Pushover curves obtained assuming a G1 distribution of the horizontal loads (-a) and corresponding damage maps obtained at failure (-b and –c). Results are depicted in terms of normalized acceleration a_g/g.

As can be noted, the active failure mechanism for the still standing part is constituted by the formation of a horizontal cylindrical hinge at the base of the pier and a sliding hinge at the crown of the arch. The failure is basically due to the overturning of the pier, as clearly visible in the damage patterns found numerically at the end of the analyses (see Figure 4-b and -c). Slightly different results have been obtained for the whole structure. In this case, there is a clear formation of an arch effect along the out-of-plane direction, favored by the continuity of the deck and the sufficient out-of-plane thickness of the bridge. As expected by the authors, the still standing part shows quite high normalized collapse accelerations, whereas the entire bridge appears much more vulnerable under horizontal loads. In case of infill with poor mechanical properties, the ultimate acceleration of the bridge is particularly low, with diffused damages observed even after the application of the self weight only.

4.1 Numerical analyses

The vulnerability of the structure has been deeply studied by means of a series of non-linear dynamic analyses conducted on both the proposed models. To this scope, two accelerograms have been adopted: (i) a spectrum-compatible accelerogram generated by the response spectrum expected (life-safety limit state: SLV, reference period: VR=100 years) for the Narni and (ii) the Umbria-Marche (1997) natural accelerogram. The horizontal as well as the vertical components have been applied at the base of both the structures. The results, in terms of displacement histories are depicted in Figure 5-a and -b, respectively for the still standing part and the whole bridge.

(-a)

(-b)

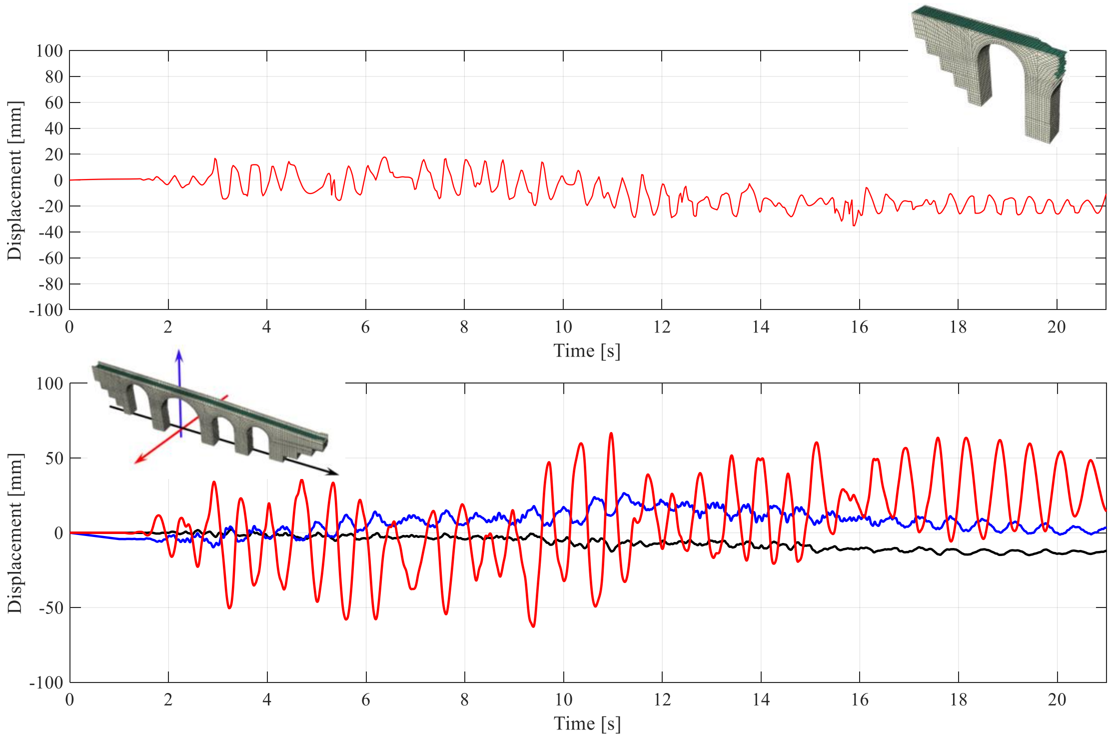


Figure 5: Relative displacements of: (-a) the keystone (still standing part) and (-b) on the top of the second arch (whole bridge).

As clearly visible in Figure 5-a, the residual relative displacement of the keystone does not exceed 2-2.5 cm. Such result suggests that some damage occurred inside the bridge as a consequence of the application of the accelerogram (see Figure 6-a), but the absolute value indicates that the displacement is quite moderate, meaning that a failure mechanism is still not active. The results obtained for the whole bridge are depicted in Figure 5-b only for the keystone of the second arch. It is interesting to notice that the damages found (see Figure 6-b) are compatible with a possible failure of the central part of the bridge, an outcome which fully justifies the hypothesis of a partial collapse caused by a seismic event. Even in this case, the residual displacements seem again relatively small (less than 5 cm), which suggest that the activation of the failure mechanism is not yet occurred completely.

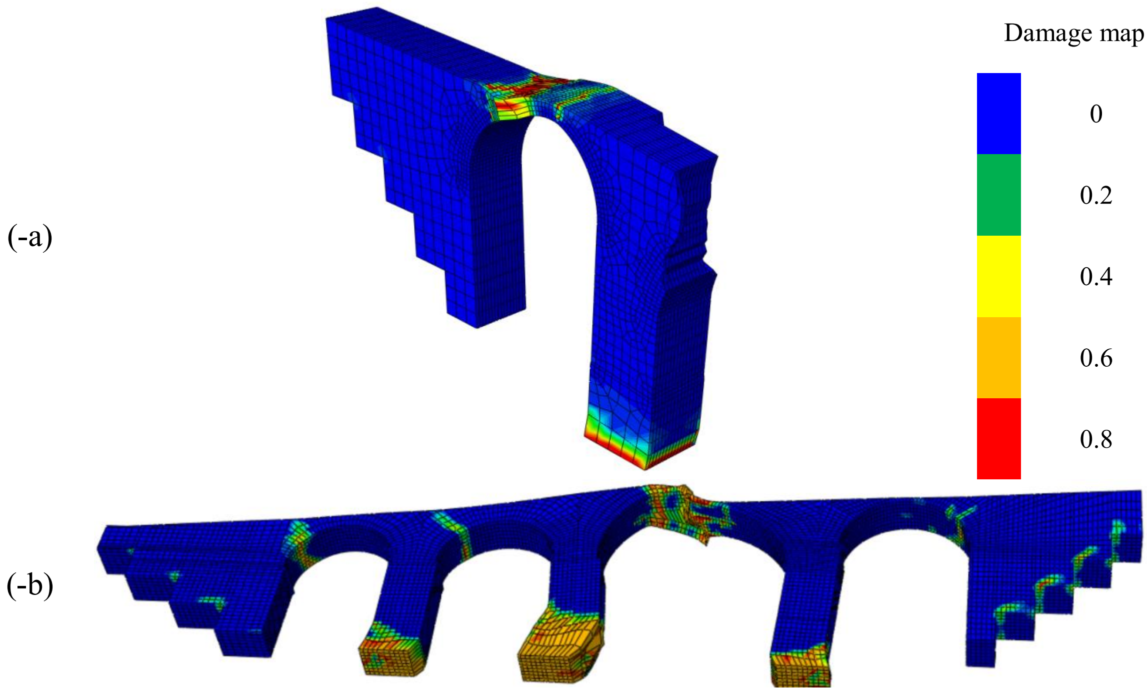


Figure 6: Tensile damage patterns obtained at the end of the non-linear dynamic analyses for: (-a) the still standing part and (-b) the whole bridge.

5 CONCLUSIONS

In the present paper, the seismic behavior of the Augustus bridge, which represents one of the most relevant Roman artwork in Italy, has been deeply investigated. In order to study the causes that led to the collapse of the structure, the bridge has been analyzed performing a series of non-linear static and dynamic analyses. As a matter of fact, several historical sources pointed out that probably it ruined some centuries ago due to a combination of different causes. In the present work, particular attention has been focused on its seismic behavior, because the high prone seismic area where it is located suggests the hypothesis that its collapse might be a consequence of an earthquake or a series of them (repeated accelerograms). The proposed hypothesis has been evaluated on the basis of the results obtained at the end of the simulations. As expected, the whole bridge resulted particularly vulnerable to dynamic excitations. The damage patterns found at the end of both the static and dynamic analyses confirmed the partial activation of a failure mechanism that involved the central arch. This finding is fully in agreement with the present configuration of the ruined bridge.

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