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In-plane and out-of-plane seismic vulnerability assessment of an ancient colonnade in the archaeological site of Pompeii (Italy)

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Abstract

The paper presents the results of an investigation carried out about the construction technique, the mechanical behaviour and the seismic response of some selected masonry remains in the archaeological site of Pompeii. In particular, the portion of the ancient colonnade dating back to the 1st century BC and located to the east of the civil forum of Pompeii is studied. Since this colonnade is a classic example of a rigid-block structure, its seismic vulnerability level is assessed performing a rigid-block model through the computer program *BrickWORK*, a tool developed by the authors. In-plane and out-of-plane non-linear analyses are carried out, considering both the horizontal uniform and the linear lateral load pattern to simulate the actions of an earthquake. In each analyzed case, the vulnerability level is assessed by detecting the collapse mechanism and the spectral acceleration of activation. Collapse mechanisms are detected by the program and graphically shown through its visual user interface. Furthermore, the influence of the joint inclination on the mechanical response of the structure is investigated considering various inclination angles of the joints between the stones of the lintel.

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Keywords: Pompeii; Colonnade; Rigid-blocks; Non-linear analysis; *BrickWORK;* Seismic vulnerability

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1. Introduction

The ancient colonnade, which originally surrounded the forum of Pompeii along three sides, was conceived as a two-storey construction in order to make it easier to collect the entrance fee to watch the shows held in the square below. As a result of the anastylosis carried out between the 1860s and the first half of the 20th century, this colonnade is composed of a double order, with Doric columns in the lower level and Ionic columns in the upper one. The white lime-stone columns are made up of dry-set drums. Probably in order to simplify the building phases and to prevent damage that may occur when continuous beams or long span beams, simply supported by the columns, are used, the lintel was made of a set of not very large nor heavy blocks, placed in contact with inclined joints. This innovative Roman technique of construction, similar to a Gerber beam, is analyzed in depth under the constructive and structural aspect. The results of the mechanical behaviour and the seismic vulnerability of the colonnade, investigated through a rigid-block model, are presented and compared to the results provided by kinematic analysis performed by-hand. Furthermore, the effectiveness of joint inclination of the lintel is investigated through a parametric analysis.

2. Historical survey

The center of meetings, business, commerce, prayer, politics and justice, the Civil Forum of Pompeii was built in the 4th century BC, i.e. the Samnite era, at the intersection of the main roads of the town (Maiuri, 1947). After the conquest of Pompeii by the Romans in the 2nd century BC, the forum was completely rebuilt and enlarged (Fig. 1). In particular, the shops and a peripheral wall were demolished. The area of the square was regularized in a rectangular shape of 143 meters by 38 meters. Various political, commercial and religious buildings were built around the square (such as the Basilica, the Curia, the *Comitium*, the Building of Eumachia, the Sanctuary of Public Lares, the *Macellum*, the Temple of Jupiter). In the Augustan age, between the end of the 1st century BC and the beginning of the 1st century AD, building works that changed the layout of the forum were started. Alongside the Temple of Jupiter, two triumphal arches, which provided the main accesses to the forum, were built in brick units covered with marble. (Maiuri, 1947).

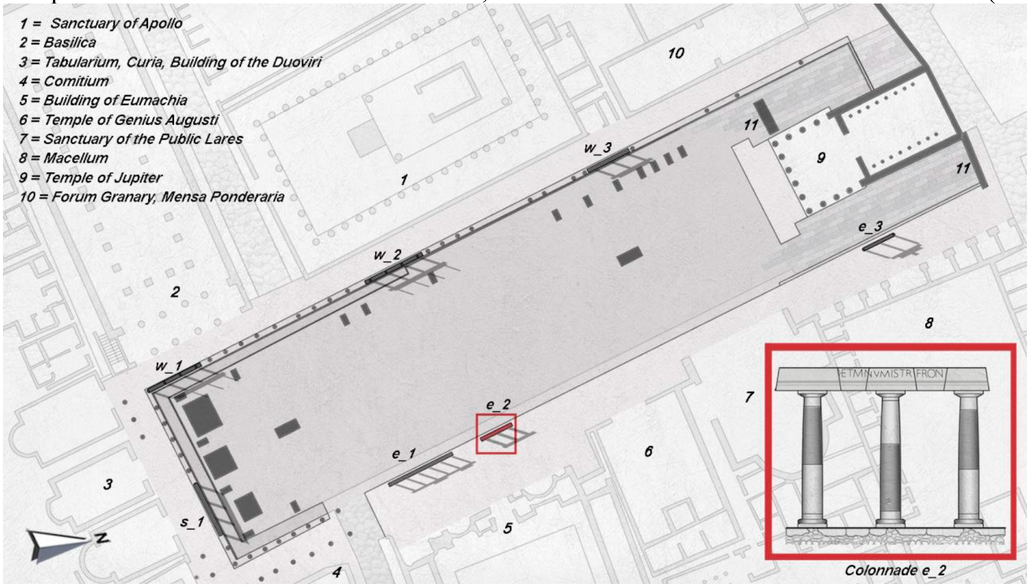


Fig. 1. Plan of the civil Forum and detail of the remain of the eastern colonnade under investigation.

The Samnite tuff colonnade was partially demolished and replaced by a new one made in travertine, supported by Doric or Tuscan smooth columns in the lower level, and by Ionic columns in the upper level. The occurrence of the 62 AD earthquake, which severely damaged various buildings in Pompeii, temporarily interrupted the construction works of the new travertine colonnade (Ruggieri et al., 2018), which was finally buried by the 79 AD eruption of Mount Vesuvius.

The former excavations began in 1738 by the will of Charles of Bourbon, and they suddenly highlighted objective difficulties relating to these pioneering works. anyway, in 1870 the first systematic campaign was conducted by Giuseppe Fiorelli, who organized the excavation works by dividing the city into 9 *regiones* further organized in *insulae*. Between 1924 and 1961 the works were conducted by the archaeologist Amedeo Maiuri, who brought to light many important buildings (Accademia nazionale dei Lincei, 1961).

In 1943 the archaeological site suffered severe damage caused by the bombing of the Second World War and, as a consequence, new strengthening and restoration interventions had to be executed. The eastern colonnade of the forum, where apparent rotations of the columns were clearly visible, resulted particularly damaged. Furthermore, differential translations between the column drums were observed (Ministero dei Beni Culturali, 1979-2008; De Simone, 2012).

3. Construction analysis

The load-bearing structure of the colonnade built in the Samnite era (Fig. 2a) is made of a sequence of tuff Doric fluted columns, with a base diameter of 72 cm, supporting the lintel that covers a more than three diameters long span. Excavations carried out by Maiuri in the 1970s revealed a discontinuous foundation composed of “plinths” built in nocerino tuff regular- sized blocks.

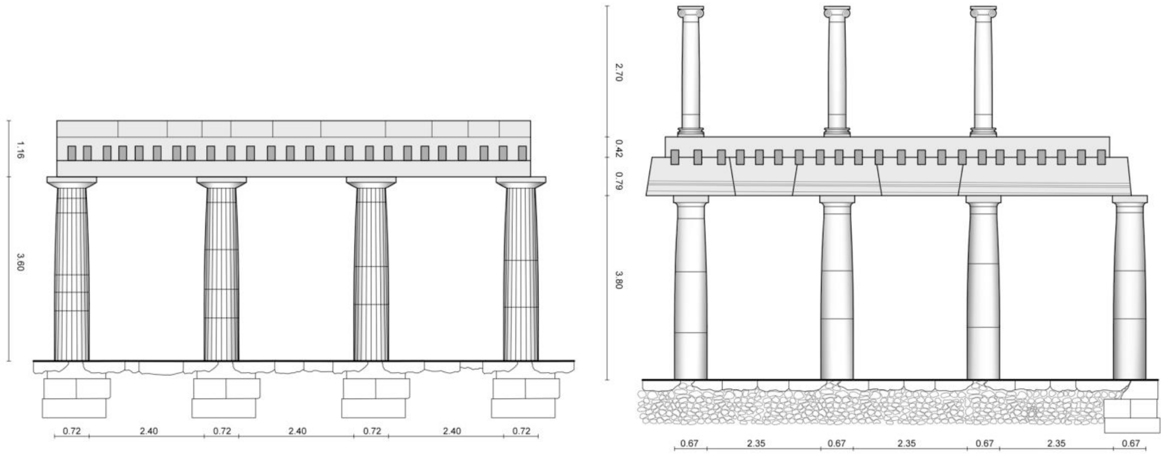


Fig. 2. a) Samnite colonnade along the southern side; b) Augustan colonnade along the west side.

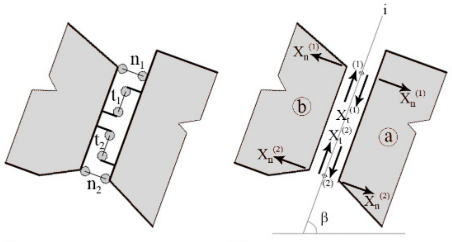
Along the side facing the inside of the colonnade, the lintel was equipped with holes to host the heads of the timber beams of a flat floor, a clear clue of a usable upper floor. The construction of the new colonnade (Fig. 2b), which replaced the Samnite one, dates back to the Augustan era. The new colonnade was completely built in travertine with a peculiar arrangement of blocks. Indeed, avoiding the use of the simple trilithic system, Pompeiians employed a “segmented lintel” composed of assembled blocks; some of them directly supported by the columns and symmetrically protruding both towards the right and the left, and characterized by inclined joints in such a way as to support a wedge-shaped central block (Fig. 2b).

The equilibrium of the central block is assured both by the use of the inclined joints and the contribution provided by the two side blocks that protrude from the supporting columns. This arrangement resembles a current Gerber beam, in which the inner discontinuities, suitably introduced into the structural model of a continuous beam placed on many supports, are realized by means of the above-mentioned inclined joints. The advantages of this structural system are twofold: first of all the bending moment to which the beam is subjected provides tensile stress at the upper edge of the two side blocks which are supported by the columns and tensile stress at the lower edge of the wedge-shaped central block (Di Pasquale, 1989), with the advantage of a reduced maximum bending moment at the midspan that, conversely, characterized the system of the simply supported beam adopted, in the former Samnite era construction. Secondly, a feasible foundation settlement allows the change of geometry of the structure without causing additional stress states. The weak link of this construction system occurs in the end bays because the end columns located at the corners of the square would be destined to an overturn due to the thrust of the wedge-shaped central block. Indeed, differently from what happens in the intermediate spans, the thrust is not counteracted by the opposite thrust of the wedge-shaped central block of the subsequent bay. therefore, to overcome this drawback, Pompeiians built the lintel of the end bays with a single block and positioned and carved it in such a way as to make it protrude from the last but one column and to support the wedge of the last but one bay block (Fig. 2b).

4. Mechanical behaviour and seismic vulnerability

Ruins of the eastern colonnade of the forum are assumed as the reference structure of this Pompeiian structural type in order to assess its seismic vulnerability. In the literature, many procedures for the analysis of masonry constructions, subject to impost movements due to soil settlement or seismic actions, usually used to investigate the behavior of specific structural systems such as arches, vaults and domes (Block at al., 2006; Betti et al., 2008; Pugi et al., 2013; Cavalagli et al., 2016; da Porto et al., 2016; Galassi et al., 2017; Pantò et al., 2017; Giresini et al., 2017; Marmo et al., 2017; Zampieri et al., 2015a,b; 2016; 2017; 2018a,b,c; 2019a,b), are present. In the specific case of the construction under investigation, the authors have used a computer program that they themselves developed to suitably model discontinuous structures detached from the original context, the peculiarity of ruins in archaeological sites. Therefore, the colonnade was analyzed through a rigid-block model performed in the *BrickWORK* software environment (Galassi et al., 2018a,b). The rigid blocks of the numerical model perfectly coincide with the travertine blocks, both as for the number and the shape and size. The contact joints between blocks exactly follow the same inclination which can be found in the actual joints of the lintel and are horizontally oriented in correspondence to the blocks forming the columns as well. According to the mechanical model implemented in our software, the contact joints between blocks are modelled using a discrete device composed of two links, orthogonal to the joint, that transfer the axial force, and two links, along the joint, that transfer the shear force (Fig. 3).

In order to interpret the mechanical behavior of this (at least originally) mortar-free construction, a tensile failure criterion has been assigned to the axial links, considering, de facto, a no-tension masonry. Conversely, infinite compression and shear strengths have been assumed, in such a way as to detect the collapse mechanism due to the sole relative rotation of blocks and to get a conservative result, which is safer.



a) b)

Figure 3. Joint device between block ‘a’ and ‘b’ of the mechanical model

According to the equivalent-static procedure, in order to detect the collapse mechanism activated by a seismic action, the analysis has been carried out merging a horizontal load condition to the gravitational one. Two horizontal load patterns have been considered: forces proportional to the masses (uniform load pattern) and actions proportional to the static forces (linear load pattern) computed, for the generic block i of the construction, using the following formulas, respectively:

$$F_i = \alpha P_i \tag{1}$$

$$F_i = k_i P_i \qquad \text{with} \qquad k_i = \frac{\alpha \cdot h_i \cdot \sum P_i}{\sum P_i \cdot h_i} \tag{2}$$

where F_i is the horizontal force applied at the center of mass of block i, α is the horizontal force factor, h_i is the height of the centroid of block i from the ground level and P_i is the weight of the block.

Two 2D-models have been analyzed. The first model is referred to the analysis of the in-plane collapse mechanism, considering the horizontal actions acting both rightward (axis +X of the mechanical model) and leftward (axis -X). Instead, the second model has analyzed the behavior of the structure subject to horizontal actions acting orthogonally to the mechanical plane (direction ±Y). The structural model subject to out-of-plane actions refers to the intermediate column of the colonnade supporting a portion of the lintel with a length equal to the column spacing. The analysis has been carried out through an incremental procedure which was interrupted when the collapse mechanism was achieved.

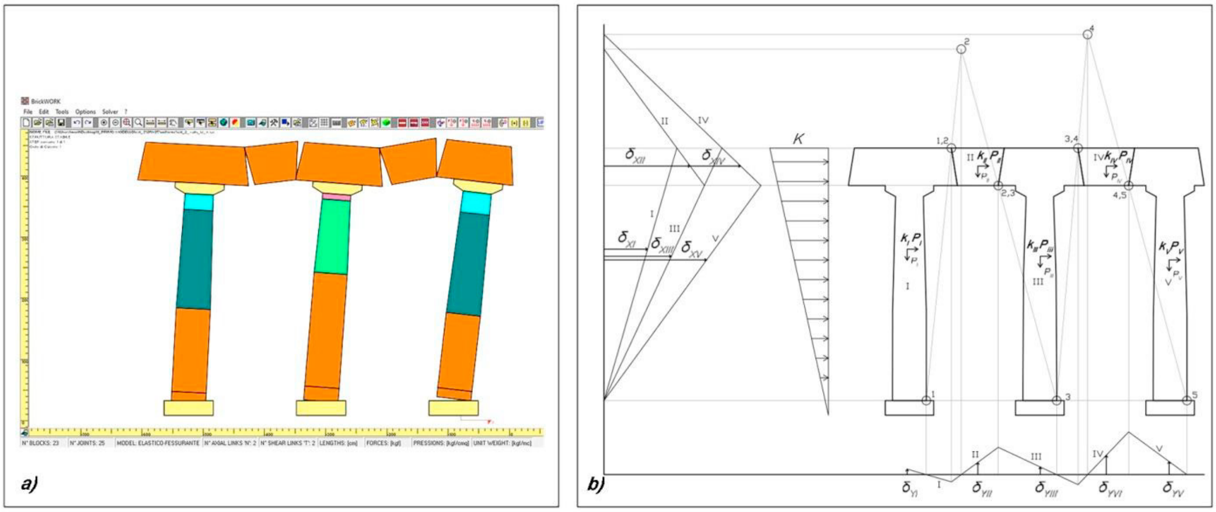


Fig. 4. Collapse mechanism activated by the horizontal linear load pattern acting along the +X direction.

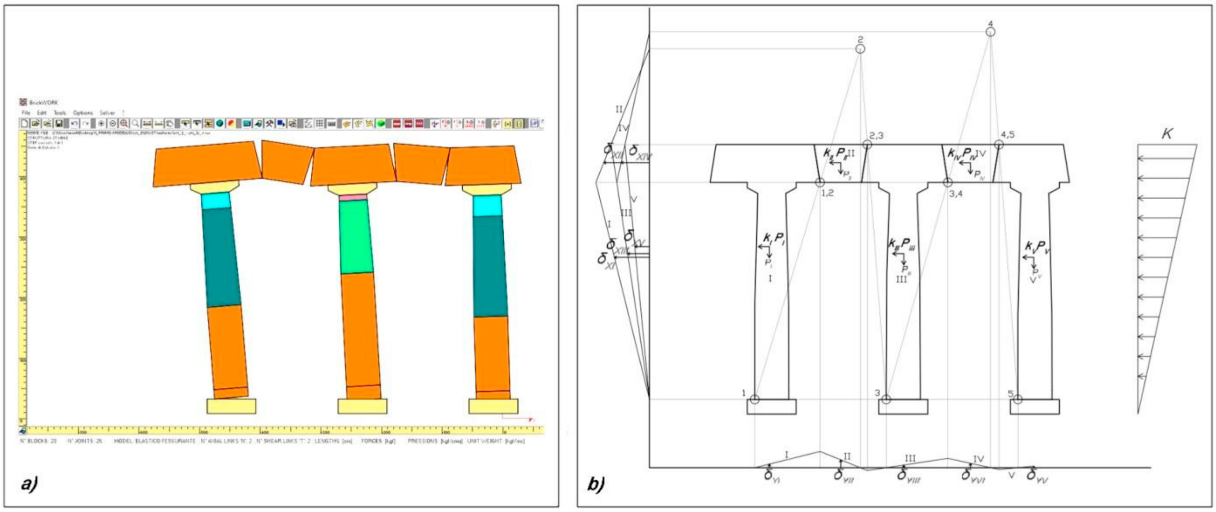


Fig. 5. Collapse mechanism activated by the horizontal linear load pattern acting along the -X direction.

Fig. 4b and Fig. 5b show the collapse mechanism activated by linearly distributed seismic forces acting in +X and -X direction, respectively. In both cases, the failure joints are the same, but the hinge points are reversed between the intrados and the extrados depending on the direction of the seismic actions. Collapse occurs due to the formation of rotation hinges at the base of the three columns and in the joints between the blocks of the lintel, alternated along the intrados and extrados.

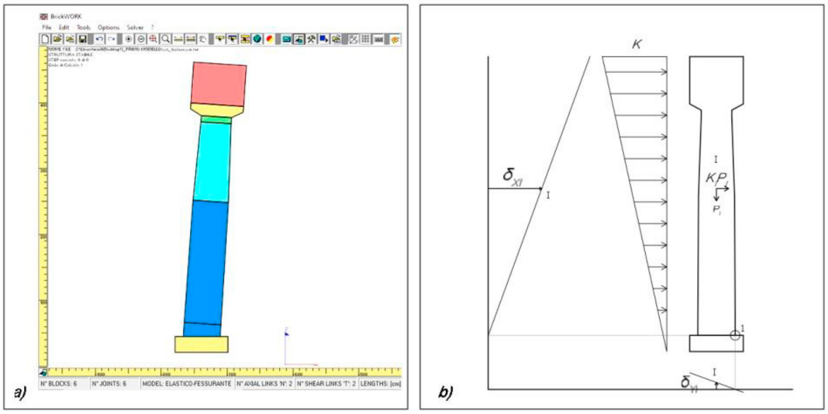
The same collapse mechanism occurs also in the case of uniform seismic forces acting along the +X and -X direction: the failure joints are the same with the hinge points inverted from the lower edge to the upper edge.

In Table 1 the results of the analysis are presented, in terms of load collapse factor α_0, total mass M, participating mass M^* and spectral acceleration of activation of the mechanism a_0^*. It is worth noting that the value of the collapse mechanism provided by the program, which computes it through an incremental analysis in large displacements, perfectly coincides with the value which one can obtain by solving the equation of principle of virtual work that, as it is well known, considers infinitesimal displacements. In this regard, the reader can compare images (a) to the corresponding images (b) of Fig. 4,5.

Table 1. Results of the analysis.

Load pattern	Earthquake direction	α_0	M	M*	a_0*
Uniform	+X	0.1252	12,952/g	9,849g	0.0165g
	-X	0.1139		9,609g	0.0153g
	±Y	0.0984	5,287/g	3,847g	0.0135g
Linear	+X	0.0947	12,952/g	9,970g	0.0123g
	-X	0.0853		9,017g	0.0122g
	±Y	0.0779	5,287/g	3,602g	0.0114

Fig. 6 finally shows the collapse mechanism activated by the linear load pattern of the seismic actions acting along the ±Y direction. Given the simplified model, the horizontal out-of-plane action provokes the overturning of the structure due to a sole hinge formation at the base of the column because the structure under analysis is a cantilever structure, which is statically determined, and has not got additional energy to counteract the thrust as in the previous case, in which a more complex mechanism may occur. Results of the analysis are reported in Table 1.



STRUTTURA STABILE

N° BLOCKS: 6 | N° JOINTS: 6 | MODEL: ELASTICO-FESSURANTE | N° AXIAL LINKS 'N': 2 | N° SHEAR LINKS 'T': 2 | LENGTHS: [cm]

Fig. 6. Collapse mechanism activated by the horizontal linear load pattern acting along the Y direction.

5. Parametric investigation

The effectiveness of the Pompeiian construction technique of the rigid-block segmented lintel with joints inclined approximately 9 degrees from the vertical axis has been investigated by means of a parametric analysis. The collapse factor of the horizontal forces has been computed as a function of the inclination angle of the joints, considering the range comprised between 0° (vertical joints) and 36° at increments of 9°.

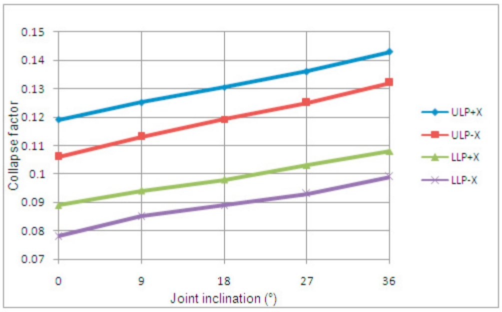


Fig. 7. Parametric analysis on the effectiveness of joint inclination.

Fig. 7 shows, for each pattern of the horizontal actions, the uniform load pattern in +X direction (ULP+X) and in -X direction (ULP-X) and the linear load pattern in +X direction (LLP+X) and -X direction (LLP+X), an increase of the performance of the structure as the inclination of the joints increases. Table 2, where the results of the parametric analysis are reported in detail, shows that the structure, regardless of the actual strength of the material, can withstand an average increase in the collapse load around 20-21% for horizontal actions in +X direction and around 25-26% for horizontal actions in -X direction.

Table 2. Results of the parametric analysis.

Collapse factor	Joint inclination [°]					Mean percentage increase [%]	Load pattern
	0	9	18	27	36		
α_0	0.119	0.125	0.131	0.136	0.143	20.17	ULP+X
	0.106	0.113	0.119	0.125	0.132	24.53	ULP-X
	0.089	0.094	0.098	0.103	0.108	21.35	LLP+X
	0.078	0.085	0.089	0.093	0.099	26.92	LLP-X

6. Conclusions

In this paper the first results of the seismic vulnerability analysis of the remains of the ancient colonnade in the civil forum of Pompeii are presented. A 2D-rigid block model describing the actual configuration of the structure has been used. The seismic action was simulated through a pattern, both uniform and linear, of in-plane and out-of-plane increasing horizontal forces. The seismic vulnerability was investigated by computing the factor of the horizontal forces that activates the collapse mechanism characterized by rotational hinges in correspondence to the contact joints between blocks. As expected, the structure resulted more vulnerable in the case of out-of-plane actions.

Currently, the authors are developing a new release of the computer program *BrickWORK* to model a 3D-rigid block structure, in order to consider the effective strength capacity of the structure that, in the reality, could develop a more complex collapse mechanism with rigid blocks partitioned by cylindrical and/or spherical hinges.

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References

Accademia nazionale dei Lincei. 1961. Saggi nell'area del Foro di Pompei, in *"Atti della Accademia nazionale dei Lincei: notizie degli scavi di antichità"*. Roma: Accademia nazionale dei Lincei. Serie VII. vol. II. pp. 371-404.

Betti, M., Drosopoulos, G.A., Stavroulakis, G.E., 2008. Two non-linear finite element models developed for the assessment of failure of masonry arches, CR Mecanique, 336(1,2), 42-53, doi.org/10.1016/j.crme.2007.10.014.

Block, P., Ciblac, T., Ochsendorf, J.A., 2006. Real-time limit analysis of vaulted masonry buildings, Comput. Struct., 84(29-30), 1841-1852, doi.org/10.1016/j.compstruc.2006.08.002.

Cavalagli, N. Gusella, V., Severini, L., 2016. Lateral loads carrying capacity and minimum thickness of circular and pointed masonry arches, Int. J. Mech. Sci., 115, 645–56, doi.org/10.1016/j.ijmecsci.2016.07.015.

Da Porto, F., Tecchio, G., Zampieri, P., Modena, C., Prota, A., 2016. Simplified seismic assessment of railway masonry arch bridges by limit analysis, Struct. Infrastruct. E., 12 (5), 567-591, doi.org/10.1080/15732479.2015.1031141.

De Simone, A., 2012. Pompei e il restauro: alcune considerazioni, in *"Atlante di Pompei"*, a cura di Gambardella C. Napoli: la scuola di Pitagora editrice.

Di Pasquale, S., 1989. L'arche-trabs del foro pompeiano. Firenze: Dipartimento di Costruzioni.

Galassi, S., Misseri, G., Rovero, L., Tempesta, G., 2017. Equilibrium analysis of masonry domes. On the analytical interpretation of the Eddy-Lévy graphical method, Int. J. Archit. Herit., 11(8), 1195-1211, doi.org/10.1080/15583058.2017.1372823.

Galassi, S., Ruggieri, N., Tempesta, G., 2018a. A novel numerical tool for seismic vulnerability analysis of ruins in archaeological sites, Int. J. Archit. Herit., 14(1), 1-22, doi.org/10.1080/15583058.2018.1492647.

Galassi, S., Ruggieri, N., Tempesta, G., 2018b. Ruins and archaeological artifacts: vulnerabilities analysis for their conservation through the original computer program BrickWORK, in: *"Structural Analysis of Historical Constructions",* Aguilar, R., Torrealva, D., Moreira, S., Pando, M., Ramos, L.F. (eds.), RILEM bookseries 18, Springer International Publishing, pp. 1839-1848. doi.org/10.1007/978-3-319-99441-3_197, Proc. of 11th International Conference on structural analysis of historical constructions (SAHC2018) (11-13 September 2018, Cusco, Perù).

Giresini, L., Sassu, M., Butenweg, C., Alecci, V., De Stefano, M., 2017. Vault macro-element with equivalent trusses in global seismic analyses, Earthquakes and Structures, 12(4), 409–423, doi.org/10.12989/eas.2017.12.4.409.

Maiuri, A., 1947. Introduzione allo studio di Pompei: il foro e i suoi monumenti. Napoli: R. Pironti.

Marmo, F., Rosati, L., 2017. Reformulation and extension of the thrust network analysis, Comput. Struct., 182, 104–118, doi.org/10.1016/j.compstruc.2016.11.016.

Ministero dei Beni Culturali, 1982. Bollettino d'arte. Sisma 1980. Effetti del patrimonio artistico della Campania e della Basilicata, in *"Bollettino d'arte",* serie VI, 2 supplemento.

Overbeck, J., 1875. Pompeji in seinen Gebäuden, Alterthümern und Kunstwerken. Leipzig: Wilhelm Engelmann.

Pantò, B., Cannizzaro, F., Caliò, I., Lourenço P.B., 2017. Numerical and experimental validation of a 3D macromodel for the in-plane and out-of-plane behavior of unreinforced masonry walls, Int. J. Archit. Herit., 11(7), 946–64, doi.org/10.1080/15583058.2017.1325539.

Pugi, F., Galassi, S., 2013. Seismic analysis of masonry voussoir arches according to the Italian building code. Ingegneria Sismica - Int. Journal of Earthquake Engineering, Patron, 30(3), 33–55.

Ruggieri, N., Galassi, S., Tempesta, G., 2018. Pompeii's Stabian Baths. Mechanical behaviour assessment of selected masonry structures during the 1st century seismic events, Int. J. Archit. Herit., 12(5), 859-878, doi.org/10.1080/15583058.2017.1422571.

Zampieri, P., Tecchio, G., da Porto, F., Modena, C., 2015a. Limit analysis of transverse seismic capacity of multi-span masonry arch bridges, Bulletin of Earthquake Engineering, 13 (5), 1557-1579. doi.org/10.1007/s10518-014-9664-3.

Zampieri, P., Zanini, M.A., Modena, C., 2015b. Simplified seismic assessment of multi-span masonry arch bridges, Bulletin of Earthquake Engineering, 13 (9), 2629-2646, doi.org/10.1007/s10518-015-9733-2.

Zampieri, P. Zanini, M. A., Faleschini F., 2016. Influence of damage on the seismic failure analysis of masonry arches, Constr. Build. Mater., 119, 343-355, doi.org/10.1016/j.conbuildmat.2016.05.024.

Zampieri, P., Zanini, M.A., Faleschini, F., Hofer, L., Pellegrino, C., 2017. Failure analysis of masonry arch bridges subject to local pier scour Eng. Fail. Anal., 79, 371-384, doi.org/10.1016/j.engfailanal.2017.05.028.

Zampieri, P., Faleschini, F., Zanini, M.A., Simoncello, N., 2018a. Collapse mechanisms of masonry arches with settled springing. Eng. Struct., 156, 363-374, doi.org/10.1016/j.engstruct.2017.11.048.

Zampieri, P., Simoncello, N., Pellegrino, C., 2018b. Structural behavior of masonry arch with no-horizontal springing settlement, Frattura ed Integrità Strutturale, 43, 182-190, doi.org/10.3221/IGF-ESIS.43.14.

Zampieri P., Cavalagli N., Gusella V., Pellegrino C., 2018c. Collapse displacements of masonry arch with geometrical uncertainties on spreading supports, Comput. Struct., 208, 118-129, doi.org/10.1016/j.compstruc.2018.07.001.

Zampieri, P., Simoncello, N., Pellegrino, C., 2019a. Seismic capacity of masonry arches with irregular abutments and arch thickness, Constr. Build. Mater., 201, 786-806, doi.org/10.1016/j.conbuildmat.2018.12.063.

Zampieri, P., Amoroso, M., Pellegrino, C., 2019b. The masonry buttressed arch on spreading support, Structures, 20, 226-236, doi.org/10.1016/j.istruc.2019.03.008.