EXPERIMENTAL INVESTIGATION OF THE SEISMIC RESPONSE OF A MULTI-DRUM COLUMN

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ABSTRACT

In this paper, the experimental results of a multiblock column have been demonstrated by the harmonic and cyclic impulse movements of the base. The tests were performed on a shaking-table with one degree of freedom at the Materials Testing Laboratory "M. Salvati" of the Polytechnic University of Bari for the rigid and deformable foundation column. Through the use of 3D printing, a staircase prototype of 6 blocks along the stem plus the capstone was built, with a base-diameter ratio of 6.5. Geometric features represent a "standard" column belonging to the classical Doric order in the Mediterranean basin. The main aim of this paper was to study the influence of deformability of the foundation on the overall dynamics of the phenomenon in order to address operational solutions that reduce the seismic vulnerability of such structures that are technically and technologically compatible with the current archaeological culture.

Keywords: multi-drum column, shaking-table testing, 3d print.

1 INTRODUCTION

The mitigation of seismic risk in archaeological sites of historical and artistic interest is a problem that requires a multidisciplinary approach as it integrates aspects of seismic hazard, vulnerability and exposure. The aim of the studies in this area is to predict and reduce the damage caused by an earthquake on multiblock stone monumental structures often of inestimable historical-artistic and anthropological value. The study presented here wants to be a contribution to the interpretation of the seismic vulnerability and to the identification of appropriate techniques to reduce the seismic risk of a specific type of monumental structures, that is, multi-block stone columns, with blocks placed one over another in simple support, representing an architectonic element widely diffused in the areas of Greek and Roman influences (Figs 1 and 2).

When these structures, predominantly intended to support gravitational loads, are subjected to low levels of horizontal excitation (such as environmental vibrations or low intensity earthquakes), they tend to respond linearly without an apparent opening of the contact sections. In this case their behavior is comparable to that of a monolithic column. Zambas (1985) [2] assumes that this condition is met for horizontal loads not exceeding approximately 4% of the total vertical load.

For more intense excitations, partializations alter the overall stiffness of the column, which in turn influences the distribution of the stresses in the elements of the structure. Also, the behavior becomes complex and the highly nonlinear response produces displacements and/or rotations of the blocks, either in group or individually [3]. As noted by Psycharis et al. [4], even during the same excitation, a multi-drum column behaves following several different 'vibrational' modes, each of which is governed by a different set of equations of motion. As the response is strongly dependent on the peculiarities of excitations, with significant sensitivity even to small changes in their parameters [5]–[8], the numerical analysis of the behavior of multiblock columns becomes extremely complex if not even impossible to develop [9].

WIT Transactions on Engineering Sciences, Vol 118, © 2017 WIT Press
www.witpress.com, ISSN 1746-4471 (on-line)
doi:10.2495/CMEM170021

Figure 1: Athens, Acropolis and Temple of Jupiter Olympus, Olympieion. (*Source: Francis Bedford, 1862 [1].*)

Figure 2: Iaat, Lebanon, Corinthian column. (*Source: photos of the early twentieth century [1].*)

To solve these problems, several numerical approaches to modeling this particular nonlinear response were proposed, with promising results from distinct element modeling solutions [10]–[13] and approximations of the individual blocks composing the column as rigid bodies [14], with sufficiently good precision and computational costs. The limits of the numerical studies are related to the inability to provide a reliable seismic response without any calibration with experimentation. This unavailability of recorded numerical response is mainly due to the difficulty in setting the values for the parameters describing block-block contact properties and the lack of a database of experimental data by type and nature of materials of such parameters.

Unlike the dynamics of the single oscillating block, multilayered columns have been subjected to limited experimentation, and, consequently, the available sources of experimental data are very limited. It should also be noted that the response of these structures is heavily dependent on their sizes and therefore experimental results on scaled models cannot be used for the study of real columns [15]. The extrapolation becomes even more problematic if the scale of the tested model is so small that the effects of the natural surface roughness are comparable to those of the sample geometry, considering that even small perturbations can govern the oscillation response of the system [16].

It has also been observed [15]–[18] that sometimes the out-of-plane precession movement may be such as to record the predominant residual deformations of the column in directions other than that of the excitation. Experimental studies have shown that the column response is sensitive to small changes in geometry and signal, so repeatability of the experiments is hardly feasible especially when the number of blocks increases, and hence the "imperfections" of the interfaces too, making the response even more unpredictable.

For these reasons, the non-linear behavior of multi-block stone monuments and any mitigation measures of seismic risk cannot be accurately numerically modeled with the few experimental data available.

It is noteworthy to recall the theoretical and experimental study faced in Blasi and Spinelli (1986) [19] regarding a rigid block oscillating on a deformable layer. In Fig. 3 the values of the free oscillation period (depending on the initial rotational amplitude) of the rigid block (Housner [5] continuous curve) are compared with those of the deformable layer block obtained for different values of the stiffness module *k* of the foundation. Horizontal trends of the curves in Fig. 3 correspond to oscillations without partialisation of the base joint: in this case, it remains in the field of elasticity, so there is a resonant frequency of the block-foundation system. It is interesting to note that as the deformability of the foundation increases (as the stiffness modulus *k* reduces) the oscillation period of the block increases and it reduces the critical angle of rotation of the block as the center of rotation moves from the edge A' to the internal point where the resulting *N* of the vertical reactions passes.

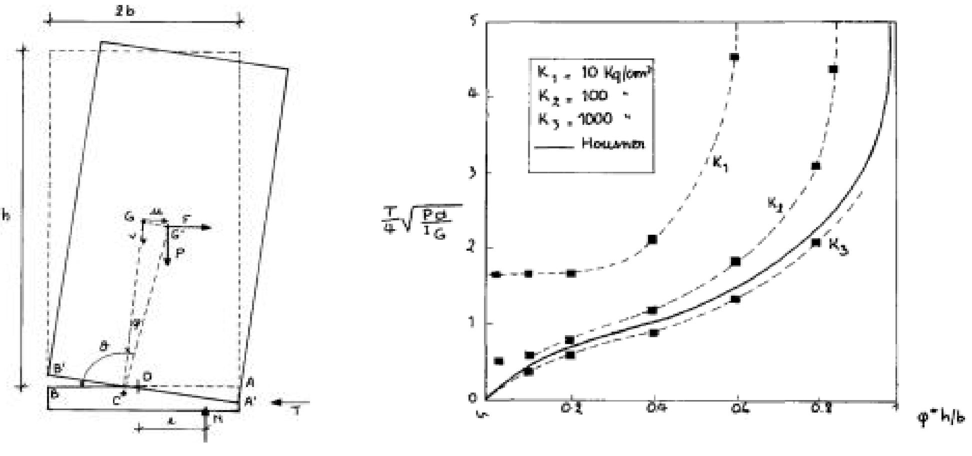

Figure 3: Rigid block on a partialised deformable layer. Free vibration periods of rigid blocks on stiff ground (continuous line) or deformable (dashed line), function of the amplitude [20].

In the following the results of experimental tests will be presented. They have been carried out in the "M. Salvati" Material Testing Laboratory of the Polytechnic University of Bari on a multiblock column arranged on a one degree of freedom shaking-table and subjected by impulsive and cyclical harmonic actions. The column was laid out once on a rigid and once on a deformable foundation with the aim:

1. To study both qualitatively and quantitatively the influence of the deformability of the foundation on the overall dynamic of the phenomenon;
2. To study both qualitatively and quantitatively the influence of the deformability of the foundation on the stability domain (as defined in Zhang and Makris [20]) of the column for impulsive loads;
3. Addressing proposals for operational solutions that reduce the seismic vulnerability of such structures that are technically and technologically compatible with the current archaeological culture, that is maximizing the integrity of the ancient material.

2 MODEL DESCRIPTION

The multiblock column used in the tests has the geometric mean characteristics of a column belonging to the classical Doric order, as reported in Rocco [21], having the following geometric features:

- Ratio of the total height of the column over the diameter measured from the base equal to 6.5;
- Number of blocks (of equal height) of the column equal to 6 plus the capital;
- The cross section has 20 circular grooves;
- A reduction of the section of the diameter upwards, that is the ratio of the diameter of the cross section at the base of the capital to the base of the column equal to 0.9;
- The blocks are in simple support without any glue or element of impediment to the relative displacement;
- Base diameter equal to 11.5 cm and a total column height of 74.75 cm.

3D printing technology has been used for building the model of the column. Both the molds (to lose) inside which the plaster was made, and the devices for accommodating the accelerometers designed for this specific test have been made. Fig. 4 shows the salient design and implementation phases of the model as well as sensors housing devices.

The specific number of blocks, six plus the capital, is not a well-defined feature of the Doric order, but a consequence of the quality and size of the raw material with which the columns were built. During the design of the sample, the number of blocks was determined by geometric regularization and uniformity along the height so as not to impose any further complication in the interpretation of the results. Particular care has been given to the realization of the contact surfaces between adjacent blocks, since imperfect contacts may significantly affect the dynamic response. The contact surfaces have been finished without impurity but with a sufficient roughness to reproduce the typical contact friction of these structures.

As mentioned in the previous paragraph, experimental tests on multiblock columns have shown the tendency of blocks to describe three-dimensional movements even if excited with monodirectional movements. There are therefore two measuring points of acceleration, at the top of the third and the sixth block, both in the direction of the stress and in the orthogonal direction.

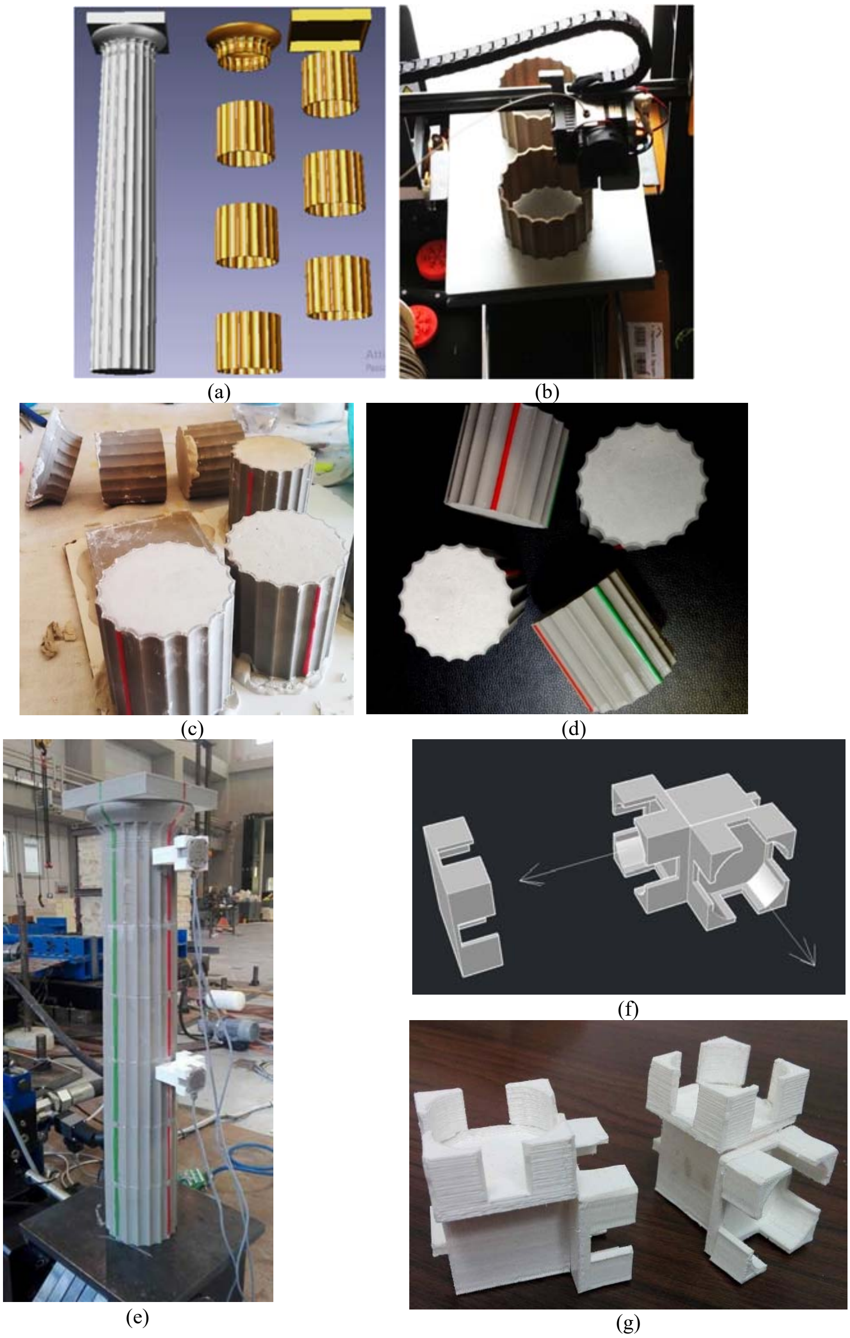

Figure 4: Design steps and realization of the columns; details of the devices realized in order to house the accelerometers. (a) Column modeling in digital environment for 3D printing; (b) 3D printing with Prusa i3 by Bq; (c) filling the mold with plaster paste; (d) regularization of block contact surfaces; (e) column on shaking table; (f), (g) modelling and printing devices for accelerometers.

3 RESULTS

Impulse tests were performed according to an incremental frequency sequence and repeated on the same configuration to evaluate the reliability of the response to the minimum or negligible input variation. As impulsive and non-random signals, reliable and stable behavior of the response to minimal variations in signals and geometry has been recorded.

Consistent with what was observed in Zhang and Makris [20], the following behavior was observed:

- The column remains intact although it recorded shifts and more or less obvious rotations of the blocks;
- The column collapses entirely after oscillating at least once around the base, i.e. collapse occurs after the base of the column exhibited one or more impacts with the support surface;
- The column collapses entirely without oscillating around the base, that is, without the base impacts the ground before the integral collapse;
- The column undergoes partial collapse;
- The number of impulsive tests carried out did not allow the entire column stability domain to be built both for a rigid basis or for a deformable base, but it was possible to record the deformable base column’s tendency to improve dynamic performance. While not having all the data necessary for the domain’s construction, it can be safely stated that the deformable base column shows an extension of the stability region (Table 1).

As previously mentioned, multicyclic harmonic analyzes (10 cycles) were performed with the following harmonic actions: 1) f = 1.00 Hz, a = 10 mm; 2) f = 1.50 Hz, a = 15 mm; 3) f = 1.75 Hz, a = 15 mm. Both have been repeated with a column on a rigid base and then on a deformable layer. The rigid base was made by a 3cm thick steel plate, while the deformable layer was made by means of a medium density cork layer placed under the base block with a thickness of 1.5 cm.

In all tests, there was a drastic reduction in the column vulnerability on deformable layer. For inputs 1 and 2, the column on the rigid base completely collapsed after the first three cycles, while the one on the deformable layer remains stable after all 10 cycles with relatively modest residual deformations.

Table 1: Experimental response of the column with a rigid base and a deformable base.

Frequency [Hz] and Amplitude [mm] of the harmonic impulse	Column on rigid base	Column on deformable base
f = 0.5 Hz; at = 45 mm	Total Collapse	Stable
f = 0.75 Hz; at = 22.5 mm	Total Collapse	Stable
f = 1.00Hz; at = 15 mm	Total Collapse	Stable
f = 1.25 Hz; at = 12.5 mm	Total Collapse	Stable
f = 1.50 Hz; at = 12.5 mm	Total Collapse	Stable
f = 1.75 Hz; at = 27.5 mm	Total Collapse	Stable
f = 2.00 Hz; at = 30 mm	Total Collapse	Stable
f = 2.25 Hz; at = 25 mm	Partial Collapse	Stable
f = 2.50 Hz; at = 30 mm	Partial Collapse	Stable

Experimental evidence showed the strong tendency of blocks to describe three-dimensional movements and for input 2 even the collapse occurred in the plane orthogonal to that of the load. This is also evident from the plots shown in Fig. 5 in which the time-histories of the acceleration are shown along the direction of the load (red) and along the orthogonal direction to the load (in green) measured in the center of gravity for input n.3.

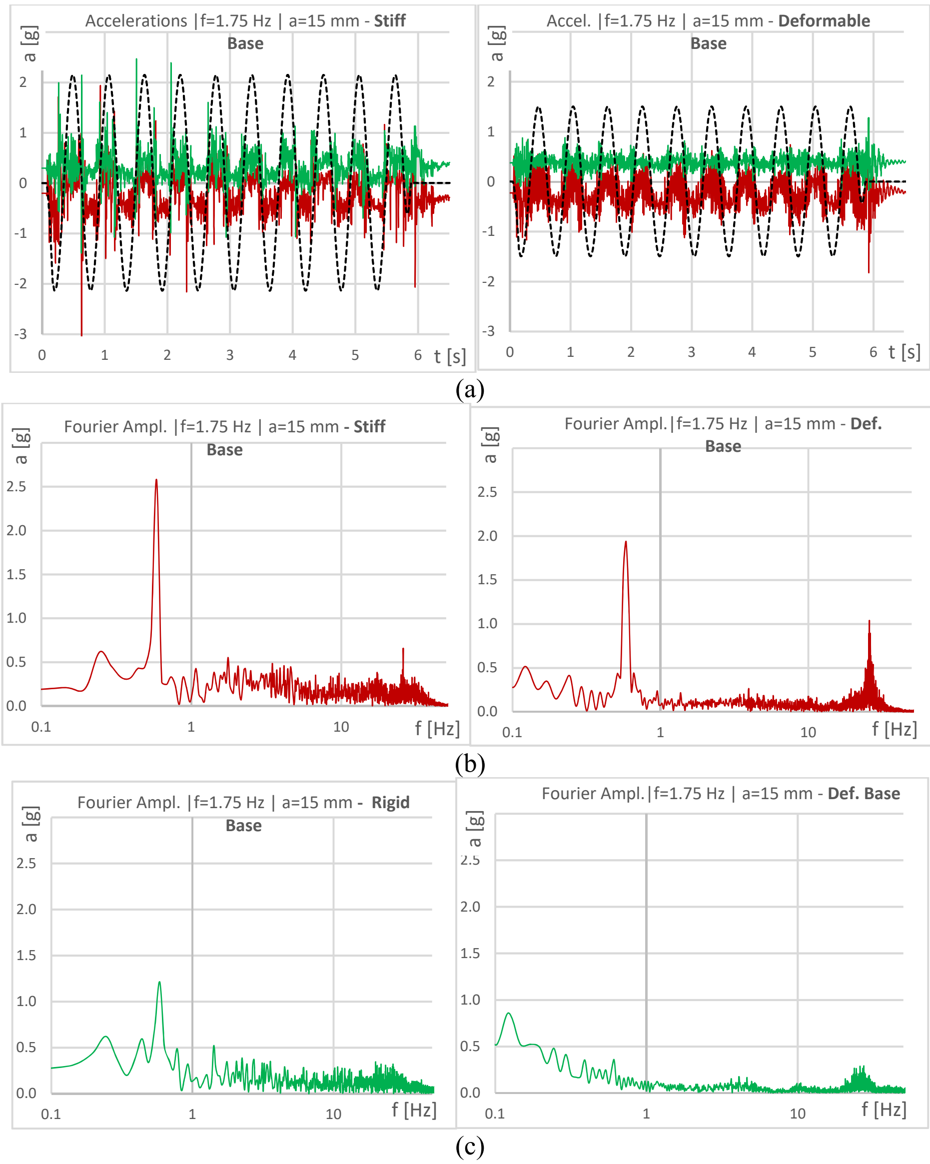

Figure 5: Comparison of the behavior recorded for the column on a rigid basis (on the left) and the one on deformable base (on the right). (a) Time-history plots of the measured accelerations, (b), (c) Fourier spectrum of the accelerations' amplitudes. Red indicates the magnitudes measured in the direction of excitation, in green those measured in the orthogonal direction.

In both directions, accelerations of the same order of magnitude are recorded. Representing them through the frequency content of the amplitudes, the excitation direction (the one in red) with respect to the orthogonal one is clear. Relative to that parallel to the direction of excitation, a peak around 0.60 Hz is recorded for the column both on a rigid basis and on a deformable layer. This may mean that we are in the range between 0.2 and 0.4 of the abscissa of the diagram shown in Fig. 3 where it is almost possible to locate an "oscillation period" for the columns.

However, the accelerations measured for the column on a deformable layer are on average 20% and 50% lower than those measured for the column on a rigid basis, respectively in the excitation direction and in the orthogonal direction.

Therefore, although qualitatively and within the scope of the conducted experimental campaign, it can be stated that placing the columns on "deformable" layers by replacing the stiff monolateral contact with a deformable layer creates an elastic behavioral pattern, at least initially. The dynamics of the model undergoes profound changes and there is a marked improvement in overall structural performance; consequently, column vulnerability is drastically reduced.

4 CONCLUSIONS

In this paper, the experimental results of a multiblock column have been were demonstrated by the harmonic and cyclic impulse movements of the base. The tests were performed on a vibrating table at a degree of freedom in the Materials Testing Laboratory "M. Salvati" of the Polytechnic University of Bari with the rigid and deformable foundation column cases. Through the use of 3D printing, a staircase prototype of 6 blocks along the stem plus the capstone was constructed, with a base-diameter ratio of 6.5. Geometric features represent a "standard" column belonging to the classical Doric order of the Mediterranean basin.

The main aim of this paper was to study the influence of deformability of the foundation on the overall dynamics of the phenomenon in order to address operational solutions that reduce the seismic vulnerability of such structures that are technically and technologically compatible with the current archaeological culture.

It is well known that the response of these structures is heavily dependent on their size and therefore the experimental results on scale models (especially if very small) cannot be used to study real columns; however, it is believed that for the purposes of this work there is a behavior that can be further deepened for larger columns. Although qualitatively and within the limits of experimentation, it can be stated that by placing the columns on "deformable" layers by replacing the rigid monolateral contact with a deformable layer, an elastic behavior pattern is created at least initially. The dynamics of the model undergoes profound changes and there is a marked improvement in overall structural performance; column vulnerability is drastically reduced. Vulnerability reduction is recorded both in the stability domains with harmonic impulses and through multicycle tests. In all cases the experimental evidence showed the strong tendency of the blocks to describe the three-dimensional movements and in many cases the collapse occurred in the plane orthogonal to the excitation.

REFERENCES

[1] Royal Collection Trust©, Her Majesty Queen Elizabeth II, 2014.

[2] Zambas, K., The Problem of the Parthenon's Earthquake Resistance: Testing the Existing Situation and the Restoration Proposals in a Stage of Preparat0'Y Studies. *Proceedings of 2nd Intern. Meeting for the Restoration of the Acropolis Monuments*, *Parthenon (Athens,1983),* Ministry of Culture: Athens, pp. 127–183, 1985.

[3] Ambraseys, N. & Psycharis, I.N., Earthquake Stability of Columns and Statues. *J. Earthq. Eng.*, **15**(5), pp. 685–710, Jun. 2011.
[4] Psycharis, I.N., Papastamatiou, D.Y. & Alexandris, A.P., Parametric investigation of the stability of classical columns under harmonic and earthquake excitations. *Earthq. Eng. Struct. Dyn.,* pp. 1093–1109, Jan. 2000.
[5] Housner, G., The behavior of inverted pendulum structures during earthquakes. *Bull. Seismol. Soc. Am.*, **53**(2), pp. 403–417, 1963.
[6] Yim, C., Chopra, A.K. & Penzien, J., Rocking response of rigid blocks to earthquakes. *Earthq. Eng. Struct. Dyn.*, **8**, pp. 565–587, 1980.
[7] Makris, N. & Roussos, Y., Rocking response of rigid blocks under near-source ground motions. *Geotechnique*, **50**(3), pp. 243–262, 2000.
[8] Psycharis, I.N. & Jennings, P.C., Rocking of slender rigid bodies allowed to uplift. *Earthq. Eng. Struct. Dyn.*, **11**, pp. 57–76, 1983.
[9] Ambraseys, N. & Psycharis, I.N., Assessment of the long-term seismicity of Athens from two classical columns. *Bull. Earthq. Eng*., **10**(6), pp. 1635–1666, Oct. 2012.
[10] Winkler, T., Meguro, K. & Yamazaki, F., Response of rigid body assemblies to dynamic excitation. *Earthq. Eng. Struct. Dyn*., **24**, pp. 1389–1408, 1995.
[11] Papantonopoulos, C., Psycharis, I.N., Papastamatiou, D.Y., Lemos, J.V. & Mouzakis, H.P., Numerical prediction of the earthquake response of classical columns using the distinct element method. *Earthq. Eng. Struct. Dyn.,* **31**(9), pp. 1699–1717, Sep. 2002.
[12] Foti, D., Ivorra, S. & Vacca, V., In-plane behavior of a masonry stone wall with complex shape blocks. *Proc. of the 16th Brick and Block Masonry Conference*, June 26–30, Padua, Italy, 2016.
[13] Foti, D., Vacca, V. & Ivorra, S., Influence of connections in the seismic behavior of trilithic large blocks masonry structures. *Proc. of the 16th Brick and Block Masonry Conference,* June 26–30, Padua, Italy, 2016.
[14] Konstantinidis, D.A. & Makris, N., Seismic response analysis of multidrum classical columns. *Earthq. Eng. Struct. Dyn.,* **34**(10), pp. 1243–1270, Aug. 2005.
[15] Mouzakis, H.P., Psycharis, I.N., Papastamatiou, D.Y., Carydis, P.G., Papantonopoulos, C. & Zambas, C., Experimental investigation of the earthquake response of a model of a marble classical column. *Earthq. Eng. Struct. Dyn.,* **31**(9), pp. 1681–1698, Sep. 2002.
[16] Palmieri, M., Penna, A. & Magenes, G., Experimental investigation of the seismic response of a multidrum stone column. *9th International Masonry Conference 2014*, Guimaraes, 2014.
[17] Papaloizou, L. & Komodromos, P., Investigating the seismic response of ancient multi-drum colonnades with two rows of columns using an object-oriented designed software. *Adv. Eng. Softw.,* **44**(1), pp. 136–149, Feb. 2012.
[18] Drosos, V., Anastasopoulos, I. & Gazetas, G., Deliverable D33 Results of the laboratory (shaking table) tests, PERPETUATE, 2012, Online. http://www.perpetuate.eu/final-results/deliverables/.
[19] Blasi, C. & Spinelli, P., Un metodo di calcolo dinamico per sistemi formati da blocchi sovrapposti. *Ingegneria Sismica*, **1**(1), pp. 12–21, 1986.
[20] Zhang, J. & Makris, N., Roking response of free-standing blocks under cycloidal pulses. *ASCE Journal of Engineering Mechanics*, **127**(5), pp. 473–483, 2001.
[21] Rocco, G., *Guida alla Lettura degli Ordini Architettonici Antichi – I. il Dorico, Liguori Editore,* Sep. 1994. ISBN 88 – 207 – 2256 – 9 (in Italian).