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Three dimensional modelling of ancient colonnade structural systems subjected to harmonic and seismic loading

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Abstract. One of the major threats to the stability of classical columns and colonnades are earthquakes. The behavior of columns under high seismic excitation loads is non-linear and complex since rocking, wobbling and sliding failure modes can occur. Therefore, three dimensional simulation approaches are essential to investigate the in-plane and out-of-plane response of such structures during harmonic and seismic loading excitations. Using a software based on the Distinct Element Method (DEM) of analysis, a three dimensional numerical study has been performed to investigate the parameters affecting the seismic behaviour of colonnades' structural systems. A typical section of the two-storey colonnade of the Forum in Pompeii has been modelled and studied parametrically, in order to identify the main factors affecting the stability and to improve our understanding of the earthquake behaviour of such structures. The model is then used to compare the results between 2D and 3D simulations emphasizing the different response for the selected earthquake records. From the results analysis, it was found that the high-frequency motion requires large base acceleration amplitude to lead to the collapse of the colonnade in a shear-slip mode between the drums. However, low-frequency harmonic excitations are more prominent to cause structural collapse of the two-storey colonnade than the high-frequency ones with predominant rocking failure mode. Finally, the 2D analysis found to be unconservative since underestimates the displacement demands of the colonnade system when compared with the 3D analysis.

Keywords: Stone; masonry; DEM; ancient colonnade; Pompeii; 3-Dimensional; seismic behavior

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1. Introduction

There are many historic monuments of high architectural and cultural values around the world that deserve protection against major earthquakes. The purpose of investigating the seismic behavior of ancient monuments (e.g. classical muilti-drum columns and colonnades) is two folds: (a) to select the suitable and effective rehabilitation techniques; and (b) to identify the mechanisms that have allowed the surviving monuments to avoid structural collapse and destruction during strong earthquakes.

Classical columns have been constructed by carefully fitted stone drums placed on top of each other, without connecting material between them. The seismic behavior of these structures is highly non-linear and complex since both rocking and sliding failure modes can occur. In fact, the drums may rock either individually or in groups resulting in several different shapes of oscillations. As a result, the analytical investigation of such structures' response is almost impossible. In addition, laboratory tests of large scale models (Drosos and Anastasopoulos 2014, 2015 and Papalou et al. 2015) are difficult and costly to perform. Analytical solutions on the dynamic behavior of infinitely rigid bodies (slender SDOF blocks) under horizontal excitations was studied by Housner (1963), who estimated the minimum horizontal acceleration of the support base that is required to overturn an infinitely rigid body. However, for multi-drum discontinuous column cases (e.g. slender MDOF colonnades), closed-form analytical solutions are not available and recourse must be had to numerical procedures to obtain their dynamic response.

Numerical simulation of ancient monuments is one of the most complicated problems in structural engineering field. This complexity results from the existence of joints as the major sources of weakness and nonlinearity. Although there are many FE analysis methods with interface elements, however, it seems that static and dynamic behavior of discontinuous ancient monuments cannot be properly investigated by such methods. This is due to the fact that these methods generally break down when a large number of discontinuities are encountered or when displacements along the discontinuities or blocks' rotations become too large.

As an alternative to the available finite element methods, the discrete element method (DEM) can be employed to simulate the nonlinear analysis of monuments. Discrete/distinct element method was initially developed for the study of jointed and fractured rock masses by Cundall (1971). In the discrete element method, large displacements and rotations between blocks, including sliding between blocks, the opening of the cracks and even the complete detachment of the blocks, and automatic detection of new contacts as the calculations' process are allowed (Itasca, 2004). This differs from the FEM where the method is not readily capable of automatically updating the contact size or creating new contacts (Asteris et al. 2015). Therefore, the DEM is particularly suitable for the analysis of masonry structures and monuments in which a significant part of the deformation is due to the relative motion between the blocks. There are various discrete element applications in the literature for both static and dynamic analysis of masonry structures (Sincraian et al. 1998, Azevedo et al. 2000, Giordano et al. 2002, Claxton et al. 2005, Sarhosis 2011, Toth et al. 2009, Sarhosis et al. 2014, Mohebkhah and Sarv-cheraghi 2014, Sarhosis and Sheng 2014). Furthermore, some researches (Psycharis et al. 2000, 2003, Papantonopoulos et al. 2002, Konstantinidis and Makris 2005, Komodromos et al. 2008, Papaloizou and Komodromos 2009, 2012, Sarhosis et al. 2015, Sarhosis et al. 2016) have shown that the DEM is also very efficient in simulating the geometric nonlinearity of ancient monuments such as classical columns and colonnades.

Psycharis et al. (2000) developed a 2D numerical model using the specialized distinct element method (DEM) software UDEC to investigate the in-plane seismic response of classical columns of two ancient temples and to identify the main factors affecting their stability. They found that ground motions with large dominant periods are more threatening to multi-drum columns than short-period ones. Also, it was observed that coupling of two columns with an architrave does not alter significantly the collapse threshold. Furthermore, they stated that the presence of geometric imperfections such as initial tilt of the column or reduced contact area may reduce significantly the stability of the system. Papantonopoulos et al. (2002) examined the efficiency of the distinct element method in predicting the 3D seismic response of multi-drum marble classical columns by comparison of numerical results with the experimental data reported in Mouzakis et al. (2002). The results showed that in spite of the sensitivity of the response to very small changes of the characteristics of the structure or the excitation, the distinct element method can capture quite well the main features of the response.

Psycharis et al. (2003) numerically studied the 3D seismic behavior of multi-drum columns of a part of Pathenon Pronaos using the distinct element method software 3DEC. They found that reinforcement of the columns drums may reduce their permanent displacements under typical earthquake motions, however, in some cases, the presence of reinforcement may be unfavorable to the safety of the structure against collapse. Konstantinidis and Markis (2005) studied numerically the seismic response of multi-drum classical columns to identify the possible advantages or disadvantages of retrofitting multi-drum columns with metallic shear links. They observed that relative sliding between drums are beneficial, since they result in a controlled rocking response of the multi-drum column. Therefore, they concluded that the installation of stiff metallic shear links between drums may have an undesirable role.

Komodromos et al. (2008) developed a specialized software using the DEM to investigate the effect of certain parameters on the seismic behavior of ancient monumental structures with monolithic or multi-drum classical columns and colonnades. The study showed that multi-drum columns could be more vulnerable to collapse under excitations of low-frequency and their failure mode is governed by rocking mode. Papaloizou and Komodromos (2009) studied the influence of the frequency content and amplitude of the ground motions on the seismic response of columns and colonnades with epistyles. They found that low-frequency earthquakes endanger both of them more than high-frequency earthquakes. Papaloizou and Komodromos (2012) investigated the stability of multi-drum columns and colonnade systems with two rows of columns under strong earthquakes and showed that the required acceleration to overturn such structures decreases as the predominant frequency of the earthquake decreases.

Psycharis et al. (2013) performed a seismic risk assessment for a multi-drum column using Monte Carlo simulation with synthetic ground motions. The obtained results provide useful information on seismic reliability of classical monuments. More importantly, in contrast to the previous belief that the vulnerability of classical monuments increases with the predominant period of the excitation, they found that it does not hold for very long periods. Drosos and Anastasopoulos (2014, 2015) conducted an experimental program on a shaking table to study the seismic vulnerability of reduced scale models of single classical temple columns and a twin-column portal. That study showed that portal structures are more stable than single columns.

Sarhosis et al. (2016) developed a 2D numerical model using the specialized DEM software UDEC to investigate the static and dynamic stability of the two-storey colonnade of the Forum in Pompeii in Italy. The structure under investigation is a two series system colonnade consisting of multi-drum columns positioned one over the other where the lower level columns support a series of both segmented and solid beams. They found that for low-frequency excitations, the primary response of the colonnade is rocking; while for high-frequency excitations, the response becomes more complicated demonstrating both sliding and rocking movements (Sarhosis et al 2016). However, it appears that the two-storey colonnade is more vulnerable to out-of-plane excitations. This is because, the colonnade would act as a slender free-standing row of columns with a large concentrated mass at the first floor level under out-of-plane inertia forces. Although, the 2D simulation approach is efficient in parametric studies of colonnades, however, it is believed that the 2D approach predicts greater stability (Psycharis et al. 2000) in comparison with the 3D simulation results. This is because, the 2D simulation cannot capture all the failure modes of real free-standing space colonnades (such as probable movements of twisting of the whole system). Therefore, a 3D simulation approach is essential to investigate the in-plane and out-of-plane responses of the colonnade, simultaneously.

The purpose of this paper is to investigate the 3D nonlinear seismic behavior of the two-storey colonnade of the Forum in Pompeii. For this purpose, a three-dimensional discrete element model is developed using the specialized discrete element software 3DEC (Itasca, 1998) for the dynamic stability analysis of the colonnade. This model is then used to compare the results between the 2D and 3D simulations emphasizing the differences for the selected earthquake records.

2. Description of the monument

The structure under investigation (Figure 1) is a two-storey colonnade of the Forum in Pompeii made of white limestone. The colonnade was erected in the main square of the ancient town where political, economic and religious events took place. To prevent the passage of the carts, the pave was raised with respect to the height of the adjacent roads by means of two steps. It is believed that originally (VII-VI century B.C.) the Forum had an irregular shape. Today, the Forum has a rectangular shape with dimensions 143 m long by 38 m wide. Probably, at the end of the II century B.C., a double row colonnade was built which was made of tuff. Some years later in 79 A.D the colonnade was reconstructed and the tuff was replaced with white limestone. The columns of the second storey followed the Ionic order while the columns of the lower storey followed the Doric order. In the second half of the 20th century, only a small part of the second storey was re-erected for educational and touristic purposes. In 1980, an earthquake produced damages in the colonnades of the Forum and it was decided to remove the beam over the second storey.

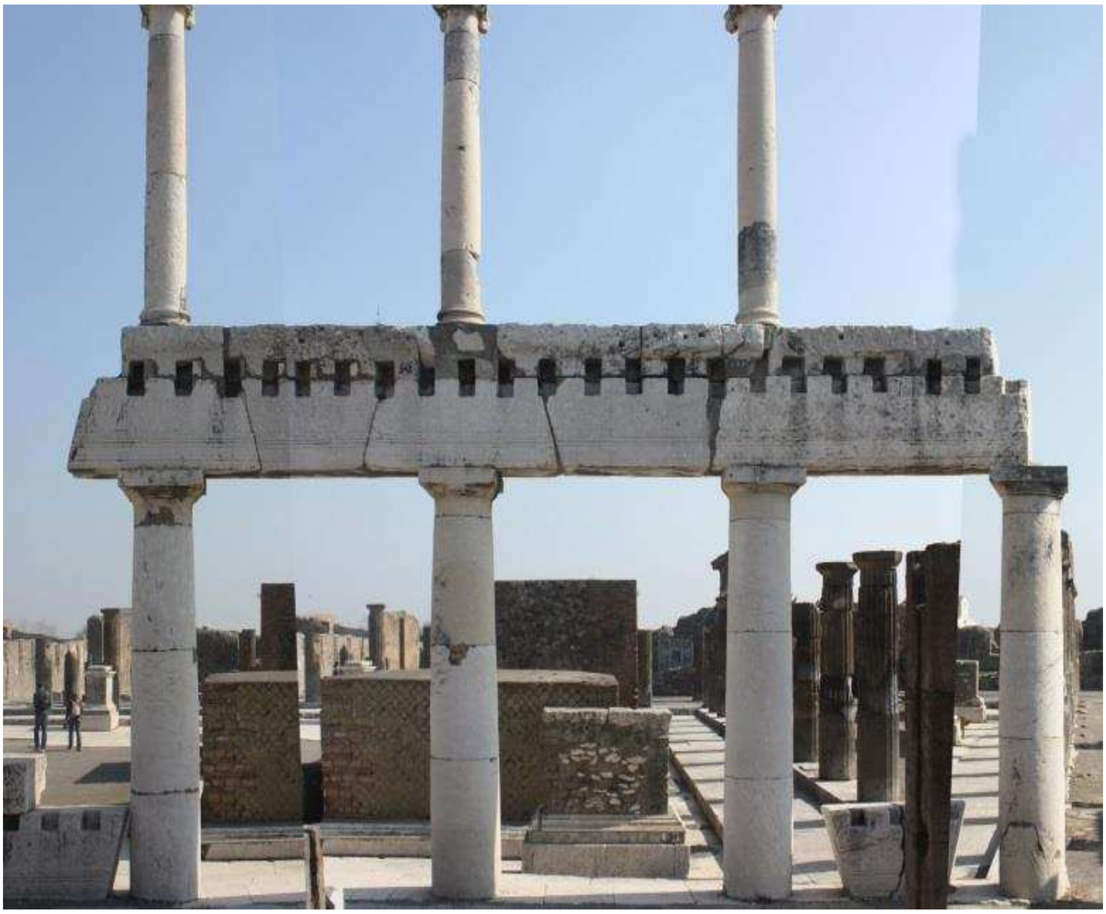
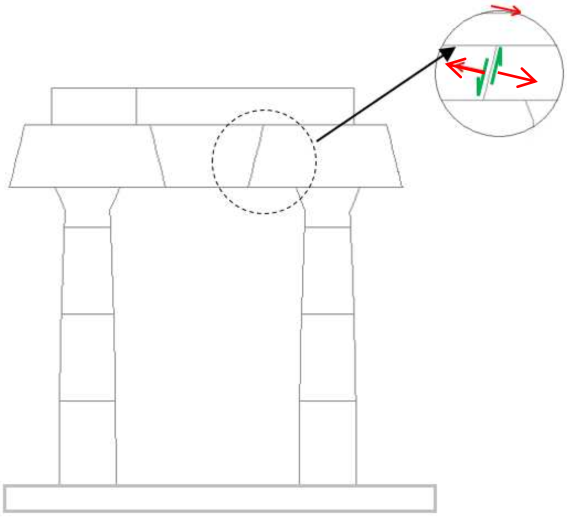
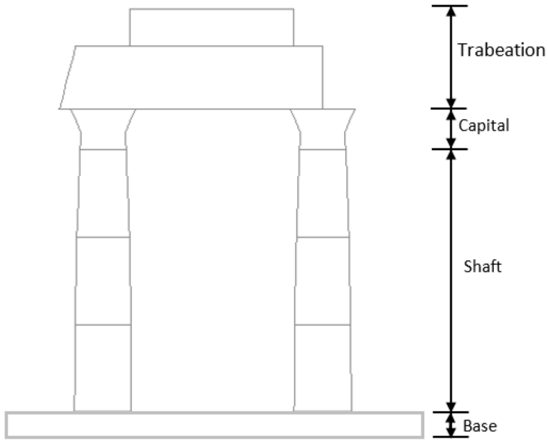


Fig. 1 Two-storey colonnade with multi-drum columns and multi-block segmented trabeations

An “innovative solution” was adopted for the construction of the trabeation. To avoid long span beams over the columns, short segments were built up providing opposing inclined patterned edges “flat arch” (Figure 2a). This solution was conceived to simplify construction phases and prevent the lifting of long span heavy beams over the columns. Blocks mutually supporting each other over inclined surfaces (keystone) induced horizontal thrust in the horizontal structures to carry loads without any tensile strength. In a fully functioning structure, each keystone pushes over the two adjacent blocks and this load is counteracted (Giamoundo et al 2014). The static problem may arise at the corners of the structure, where there is no symmetric mutual interaction and could lead to the overturning of the column. To overcome the above hurdle, the builders avoided the reduced size blocks at the end of the colonnade. Instead, a long block (solid long beam in Figure 2b), supported by the first two extremity columns has been placed (Sarhosis et al. 2016). In that way, the horizontal thrust, not counteracted by the contiguous blocks, missing, was counteracted by two columns, so halving the horizontal thrust. The examination of the methods employed by the ancient builders revealed the continuous research and evolution in design of structures against earthquakes (Adam 1989; Maiuri 1942).


(a) Flat arch (segmented beam)



(b) Solid long beam

Fig. 2 Different construction methods at the trabeation of the Forum in Pompeii

3. Overview of 3DEC for modelling masonry

3DEC is an advanced numerical modelling code based on DEM for discontinuous modelling and can simulate the response of discontinuous media, such as masonry, subjected to either static or dynamic loading. When used to model masonry, the units (i.e. stones) are represented as an assemblage of rigid or deformable blocks which may take any arbitrary geometry. Typically, rigid blocks are adequate for structures with stiff, strong units, in which deformational behaviour takes place at the joints. For explicit dynamic analysis, rigid block models run significantly faster. For static problems, this computational advantage is less important, so deformable blocks are preferable, as they provide a more elaborate representation of structural behaviour. Deformable blocks, with an internal tetrahedral FE mesh, were used in the analyses reported herein. Joints are represented as interfaces between blocks. These interfaces can be viewed as interactions between the blocks and are governed by appropriate stress-displacement constitutive laws. These interactions can be linear (e.g. spring stiffness) or non-linear functions. Interaction between blocks is represented by set of point contacts, of either vertex to face or edge to edge type (Figure 3). In 3DEC, finite displacements and rotations of the discrete bodies are allowed. These include complete detachment between blocks and new contact generation as the calculation proceeds. Contacts can open and close depending on the stresses acting on them from the application of the external load. Contact forces in both the shear and normal direction are considered to be linear functions of the actual penetration in shear and normal directions respectively (Itasca, 1998). In the normal direction, the mechanical behaviour of joints is governed by the following equation:

$$\Delta\sigma_n = -JK_n.\Delta u_n \tag{1}$$

where JK_n is the normal stiffness of the contact, $\Delta\sigma_n$ is the change in normal stress and Δu_n is the change in normal displacement. Similarly, in the shear direction the mechanical behaviour of mortar joints is controlled by a constant shear stiffness JK_s using the following expression:

$$\Delta \tau_s = -JK_s . \Delta u_s \tag{2}$$

where $\Delta\tau_s$ is the change in shear stress and Δu_s is the change in shear displacement. These stress increments are added to the previous stresses, and then the total normal and shear stresses are updated to meet the selected non-elastic failure criteria, such as the Mohr-Coulomb model.

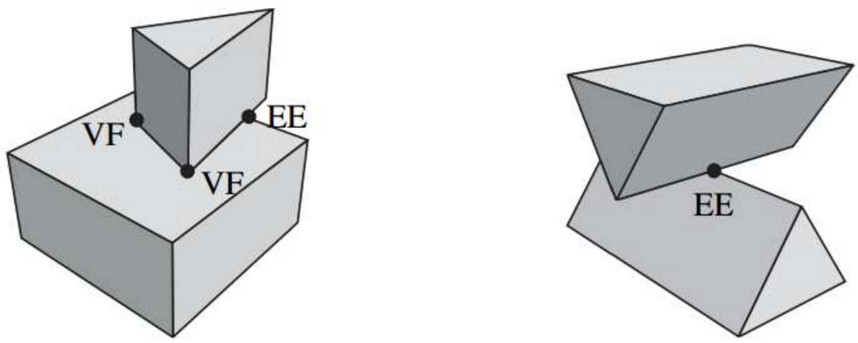


Fig. 3 Representation of block interaction by elementary vertex-face (VF) and edge-edge (EE) point contacts in 3DEC (Lemos 2007)

The calculations are made using the force-displacement law at all contacts and the Newton's second law of motion at all blocks. The force-displacement law is used to find contact forces from known displacements, while the Newton's second law governs the motion of the blocks resulting from the known forces acting on them. Convergence to static solutions is obtained by means of adaptive damping, as in the classical dynamic relaxation methods. Figure 4 shows the schematic representations of the calculations taking place in 3DEC analysis.

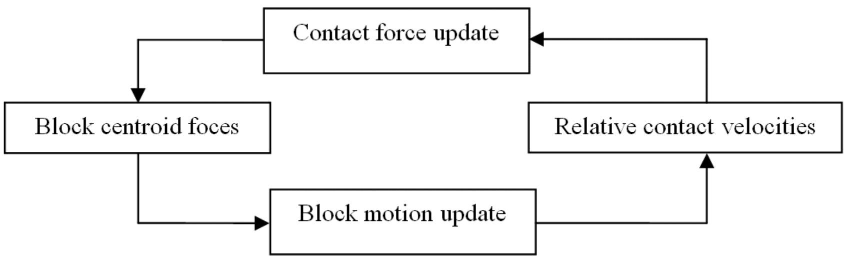


Fig. 4 Calculation cycle in 3DEC (Itasca, 1998)

4. Development of the computational model

4.1 Model geometry

Geometric models representing the two-storey colonnade of the Forum in Pompeii were created in 3DEC (Figure 5). Each stone of the monument (i.e. drum of the column and stone block of the trabeation) represented by a deformable block separated by zero thickness interfaces at each joint. Also, each block was internally discretized into finite-difference zone elements, each assumed to behave in a linear elastic manner, characterized by elastic density and elastic properties. In practice, the stresses in the stone blocks would be well below their strength limit and so no significant deformation would be expected to occur in them (Sarhosis et al. 2016). To replicate this, a coarse internal mesh was used and stone material parameters were specified to ensure that no block deformation would occur; yet the software was enabled to calculate the theoretical stresses in each zone element. Although it was possible to use a rigid block model in this study, however, for such models just a displacement value is calculated for each individual block which may be insufficient for displaying the displacement contours of the rotating blocks within the architraves. The zero thickness interfaces between each block were modelled using 3DEC's elastic perfectly plastic Coulomb criterion defined by: the elastic normal stiffness (JK_n); the shear stiffness (JK_s); and the joint angle of friction (Jfric).

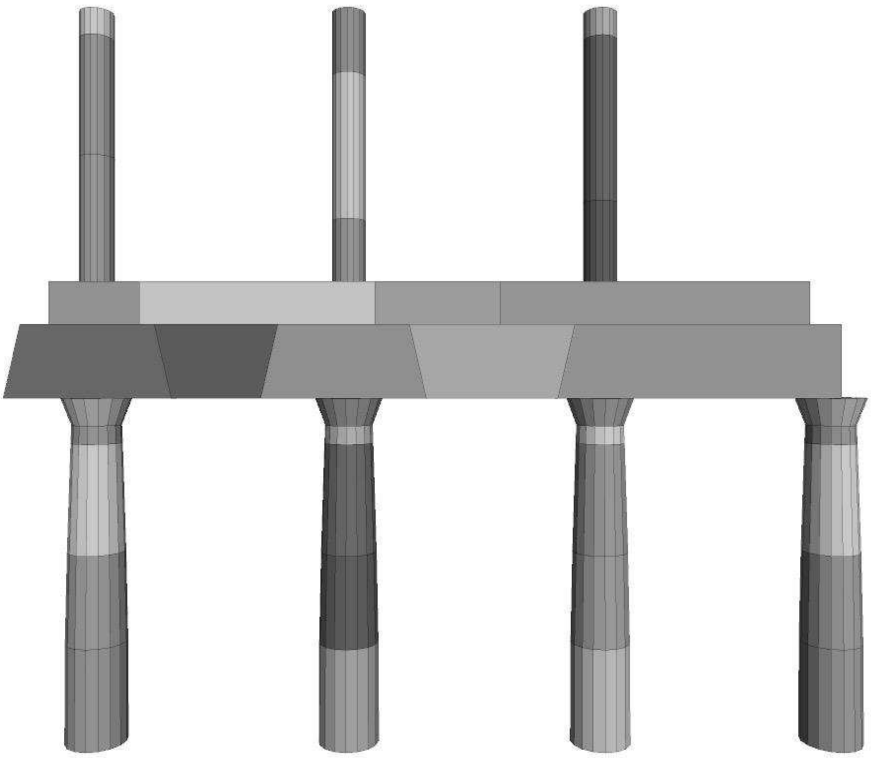


Fig. 5 Geometry of the two storey colonnade of the Forum of Pompeii

4.2 Material properties

Material properties to be inputted to the numerical model are important for the accurate prediction of the mechanical behaviour of structures subjected to external loads. Since mechanical tests on archaeological structures are not permitted, material properties for the stone blocks and joints were obtained from experimental tests carried out on similar stones and joints (Kastenmeier et al. 2010 and Angrisani et al. 2010). The material parameters used for the development of the computational model are shown in Tables 1 and 2. Since the colonnade of the Forum in Pompeii is a mortarless (dry-stacked) block masonry system, the joint tensile strength (Jten), joint cohesive strength (Jcoh) and the joint dilation angle (Jdil) were assumed to be zero.

Table 1 Properties of the limestone blocks

Unit Weight d [kg/m^3]	Young Modulus E [GPa]	Shear Modulus G [GPa]	Bulk Modulus K [GPa]	Poisson's Ratio v [-]
2,680	40	16	27	0.25

Table 2 Properties of the joint interfaces

Normal Stiffness JK_n [GPa/mm]	Shear Stiffness JK_s [GPa/mm]	Joint friction angle Jfric [degrees]
4	2	30°

4.3 Loading procedure

The bottom edges of the computational model were fixed and self-weight effects were assigned as gravitational load. The analysis was carried out sequentially. First, each model was brought to equilibrium under its own dead weight. Then, external loading has been applied to the structure. However, it should be mentioned that no attempt made to simulate the construction sequence at this study. The influence of the construction sequence on the stability of the colonnade has been extensively studied at Sarhosis et al. (2016). Horizontal displacements at the upper part of the top column of the colonnade have been recorded. The results of the response of the structure under seismic load are presented below.

4.4 Damping

The solutions were obtained by a process of dynamic relaxation, using scaled masses and artificial damping. Hence, viscous mass proportional damping was used, with an adaptive scheme that updates the damping coefficient step-by-step based on the dominant frequency of the structure from the Rayleigh quotient (Sauvé & Metzger 1995). Also, in the proposed numerical model, the default ratio of the damping and the rate of change of nodal kinetic energy is 0.5. However, from the numerical simulations it was found that with this default ratio the convergence of the solution was very slow near collapse: the structure already unstable under the given loads, but the damping did not allow the development of the failure. Therefore, in this study, the ratio of damping was decreased to 0.1.

5. Response to harmonic excitation

In order to investigate the impact of the excitation frequency in the collapse mechanism, harmonic excitations with the frequency ranged from 1 to 7 Hz and the amplitude of the base acceleration ranged from 1.7 to 80 m/s^2 were applied to the two-storey colonnade. The initial analysis results show that the high-frequency motion requires large base acceleration amplitude to lead to the collapse of the colonnade in a shear-slip mode between the drums. Therefore, it can be concluded that the motion frequency plays a prominent role in the dynamic response of the structure. From Figure 6 it can be seen that harmonic wave with larger acceleration amplitude leads to larger deformations.

Also, the amplitude of the base acceleration in the longitudinal direction (i.e. x-direction) was increased by small steps until collapse of the structure occurred. In this regard, the safe-unsafe threshold of the acceleration amplitude of the two-storey colonnade in Pompeii was determined for each excitation frequency as shown in Fig. 7. Figure 7 shows for each pair of values for the excitation frequency and amplitude, whether the colonnade collapsed or not. The amplitude required to cause collapse should be larger than the safe-unsafe threshold. Based on this restriction, the safe-unsafe boundary estimated. As shown in Figure 7, the threshold of acceleration amplitude causing collapse significantly reduces as the frequency of the harmonic excitation reduces. Low-frequency harmonic excitations are more prominent to cause structural collapse of the two-storey colonnade than the high-frequency ones. Therefore, apart from the base acceleration, the motion frequency has also an influencing role in the dynamic response of the structure. It should also be mentioned that there may be the case that the colonnade collapsed at a certain acceleration level, whereas it remained stable for larger amplitude input. For such cases, the safe-unsafe boundary was determined by the smaller acceleration causing collapse.

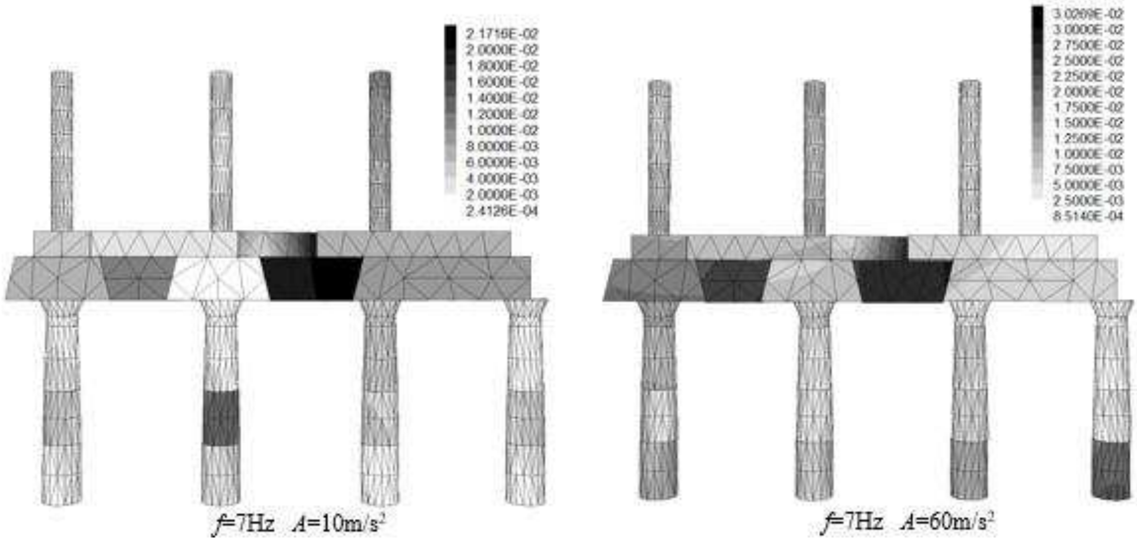


Fig. 6 Contours of the final displacement (m) of the excitations under different acceleration levels

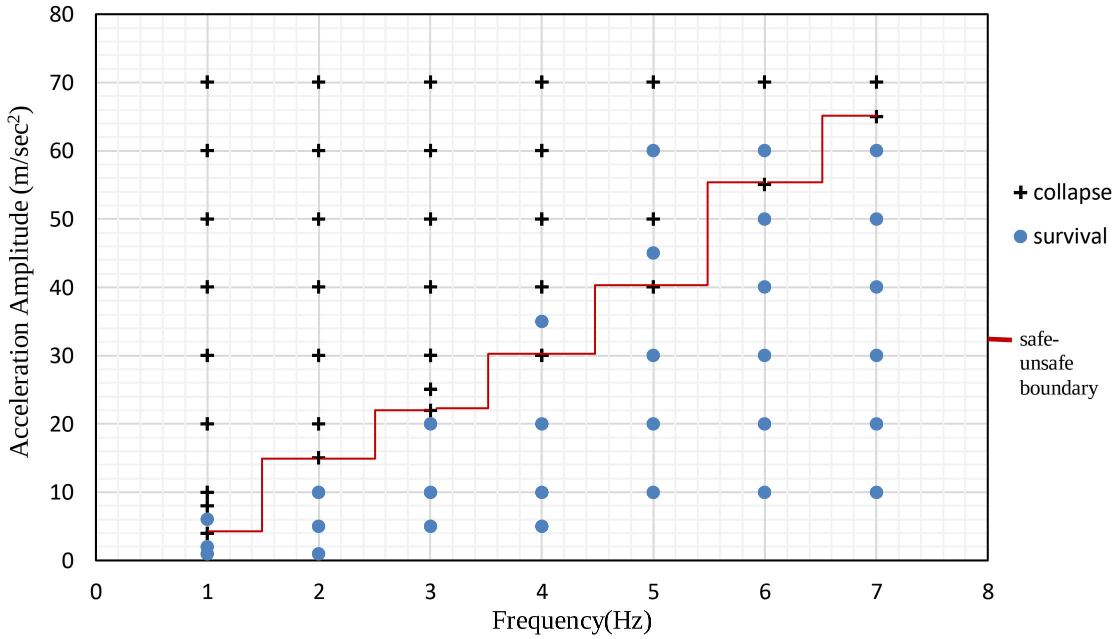


Fig. 7 Safe-unsafe boundary under harmonic wave applied in x-direction

Figure 8 shows that blocks of the lower beams and columns are subjected to larger displacements than the upper beams and columns.

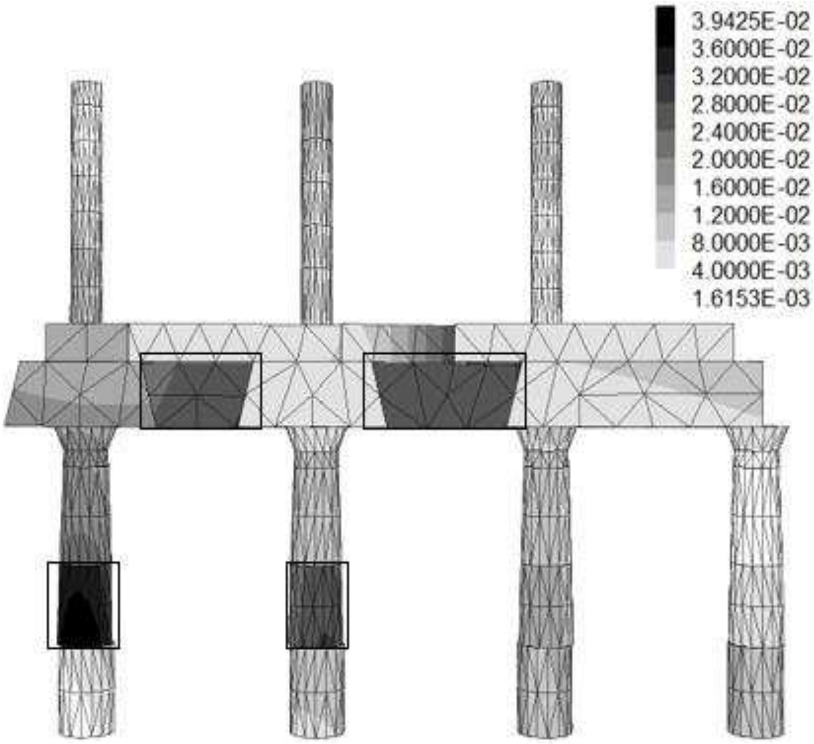


Fig. 8 Location of the blocks with large displacement under harmonic wave applied in x-direction

To investigate the behaviour of the two-story colonnade to out-of-plane excitation, it was also subjected to the harmonic excitation in the perpendicular y-direction. The frequency of the excitation ranged from 1 to 7 Hz and the amplitude of the base acceleration ranged from 1.7 to 80 m/s^2. The results of y-direction harmonic excitation presented in Fig. 9, demonstrate that similar to the x-direction excitation, the two story colonnade is more vulnerable to low-frequency motions with predominant rocking failure mode.

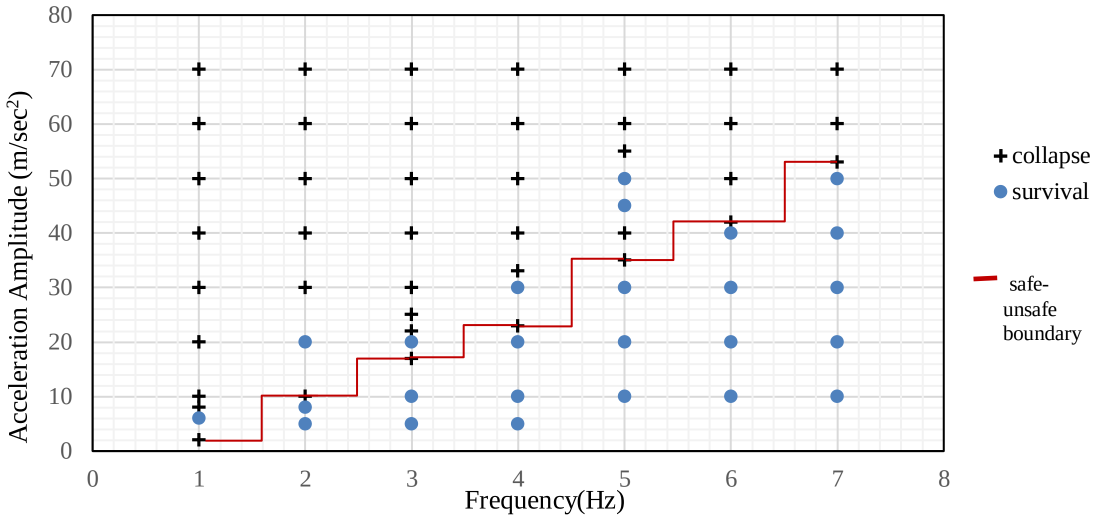


Fig. 9 Safe-unsafe boundary under harmonic wave applied in y-direction

The safe-unsafe thresholds of the harmonic acceleration amplitude of the colonnade under in-plane and out-of-plane excitations are shown in Fig. 10. From Fig. 10, it can be seen that the two-story colonnade is more vulnerable to the out-of-plane harmonic excitation.

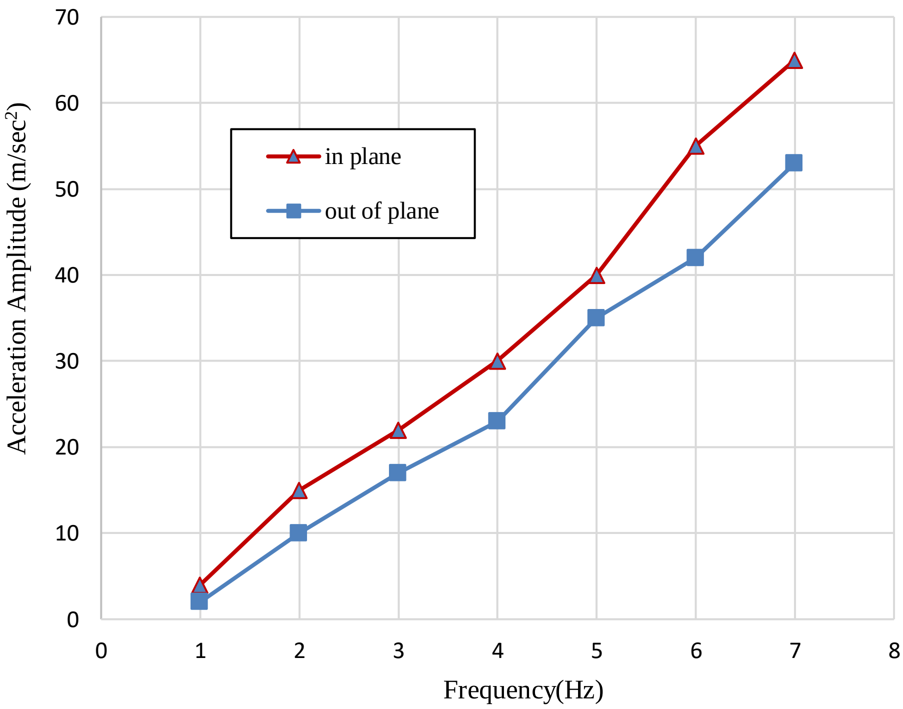


Fig. 10 Safe-unsafe boundaries under in-plane and out-of-plane excitations separately

6. Response to seismic excitations

Four earthquake records with different characteristics such as the magnitude, the predominant period, the frequency and the type of seismic wave (sinusoidal or not) were used in order to investigate the stability of the two-storey colonnade to various seismic excitations. Earthquake excitations were selected to cover a wide range of recorded ground motions with different characteristics and not representative of the specific site in Pompeii. The seismic action applied to the base block of the model. The time histories of the acceleration of the records' components that were applied in the colonnade are shown in Figure 11. Also, the response spectra are presented in Figure 12. The four earthquake records selected for this study are as follows:

- The Bucharest 1977 earthquake took place in the region of Vrancea and it was one of the worst earthquake disasters of the 1970s. The earthquake had a magnitude of Ms = 7.2 Richter and the epicenter was at 94 kilometers local depth. This earthquake has been selected due to its large-amplitude quasi-sinusoidal pulse.
- The Irpinia earthquake 1980 occurred in the Irpinia region in Southern Italy. Its magnitude was Ms = 6.9 Richter and resulted due to the Irpinia fault activation which is known as one of the most active faults in the world.
- The Kalamata 1986 earthquake occurred in Greece and had a magnitude equal to Ms = 6.2 Richter. It contains near field strong motion data that caused considerable damage to the buildings of the city of Kalamata.
- The L'Aquila 2009 earthquake occurred in the region of Abruzzo, in central Italy. The main shock was rated Ms = 6.3 on the moment magnitude scale; its epicentre was near L'Aquila, the capital of Abruzzo, which together with surrounding villages suffered considerable damage.

An earthquake has a much richer frequency spectrum than sinusoidal signals. Moreover, the four earthquakes that were taken into account can be hardly considered as representative given the complex dynamic and strongly non-linear behaviour of this kind of systems. Of course, these approaches were relatively recently applied to this kind of structures, but when general conclusions are to be made regarding the dynamic behaviour and resistance to collapse, they are necessary. Figure 12 shows the corresponding acceleration response spectra for 5% damping ratio.

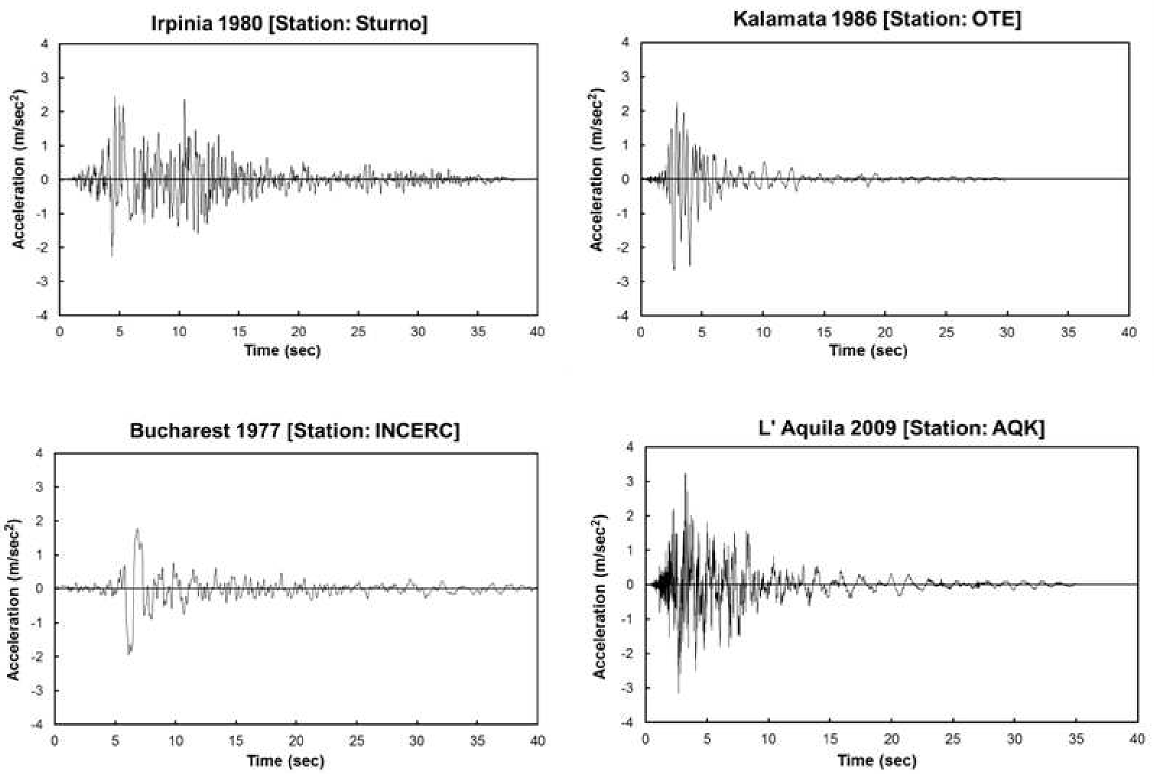


Fig. 11 Acceleration time histories of the selected earthquake records applied on the monument

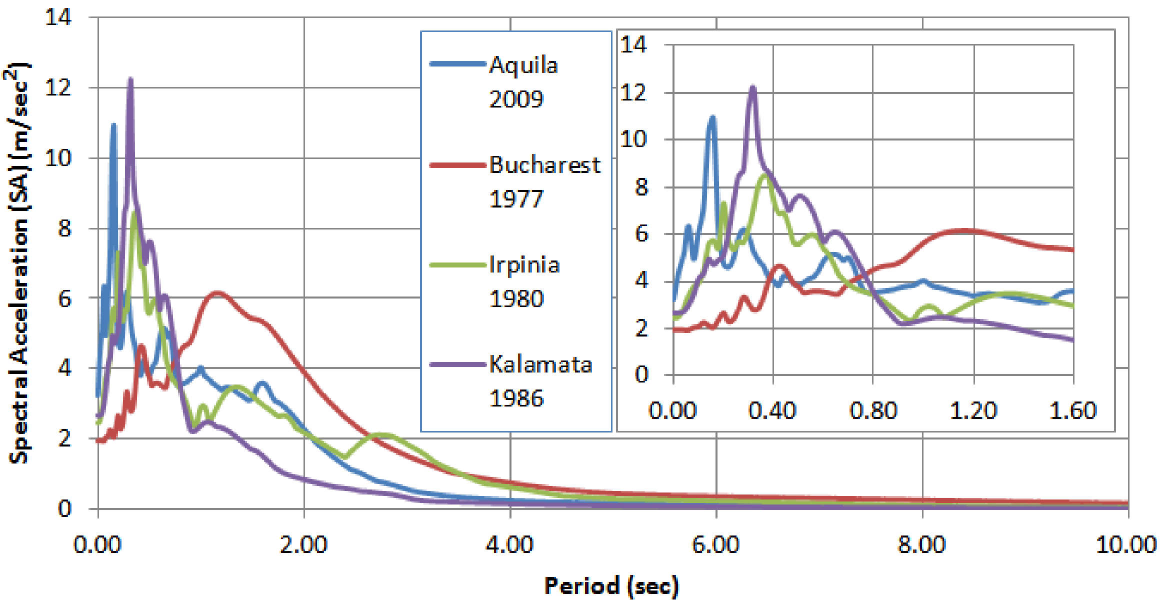


Fig. 12 Acceleration response spectra for 5 % damping ratio of the base motions

6.1 Structural behavior of the colonnade subjected to in-plane and out-of-plane excitations

Figure 13 compares the maximum displacement of the capital against the peak ground acceleration for the four earthquakes acting in the in-plane direction (xx’). From Figure 13, the two-storey colonnade experiences larger displacements under the Bucharest, 1977, ground motion excitation and fails at PGA of about 1 m/s^2. This behavior may be attributed to the existence of low-frequency pulses in the earthquake ground motion which leads to a rocking failure mode. Similar behavior is also observed under the L'Aquila, 2009, ground motion which failed at PGA of about 1.8 m/s^2. However, the colonnade fails at much higher PGA under the other ground motions. The maximum lateral (out-of-plane) displacements (i.e. y-disp) of the colonnade under the in-plane excitations have also been recorded and plotted in Fig. 13 for comparison. Fig. 13 shows that except for the Kalamata, 1986, earthquake record, the maximum out-of-plane and in-plane displacements are of the same order. This means that due to the presence of some eccentricities and applied torsional moments, the colonnade structure vibrates bidirectionally under the in-plane excitations.

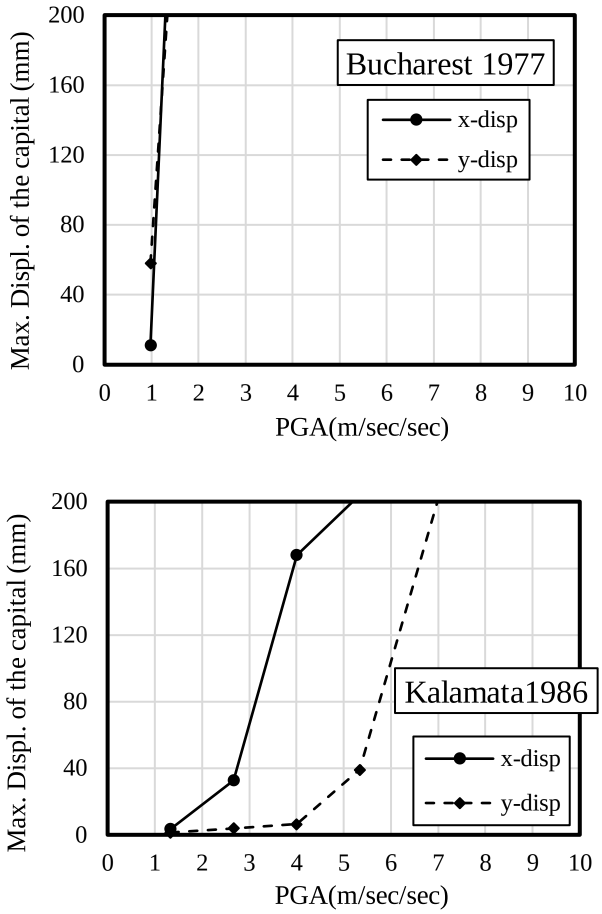


Fig. 13 Maximum displacement of the capital against peak ground acceleration (in-plane excitation)

Similar to Fig. 13, Fig. 14 compares the variation of maximum displacement of the capital against the peak ground acceleration for the four earthquakes acting in the out-of-plane plane direction. As can be seen, the colonnade is again more vulnerable to the Bucharest and the L'Aquila records under the out-of-plane excitation. Furthermore, Fig. 14 reveals that there is also a degree of coupling between the in-plane and out-of-plane motions of the colonnade under the out-of-plane excitations and the perpendicular displacements are of the same order.

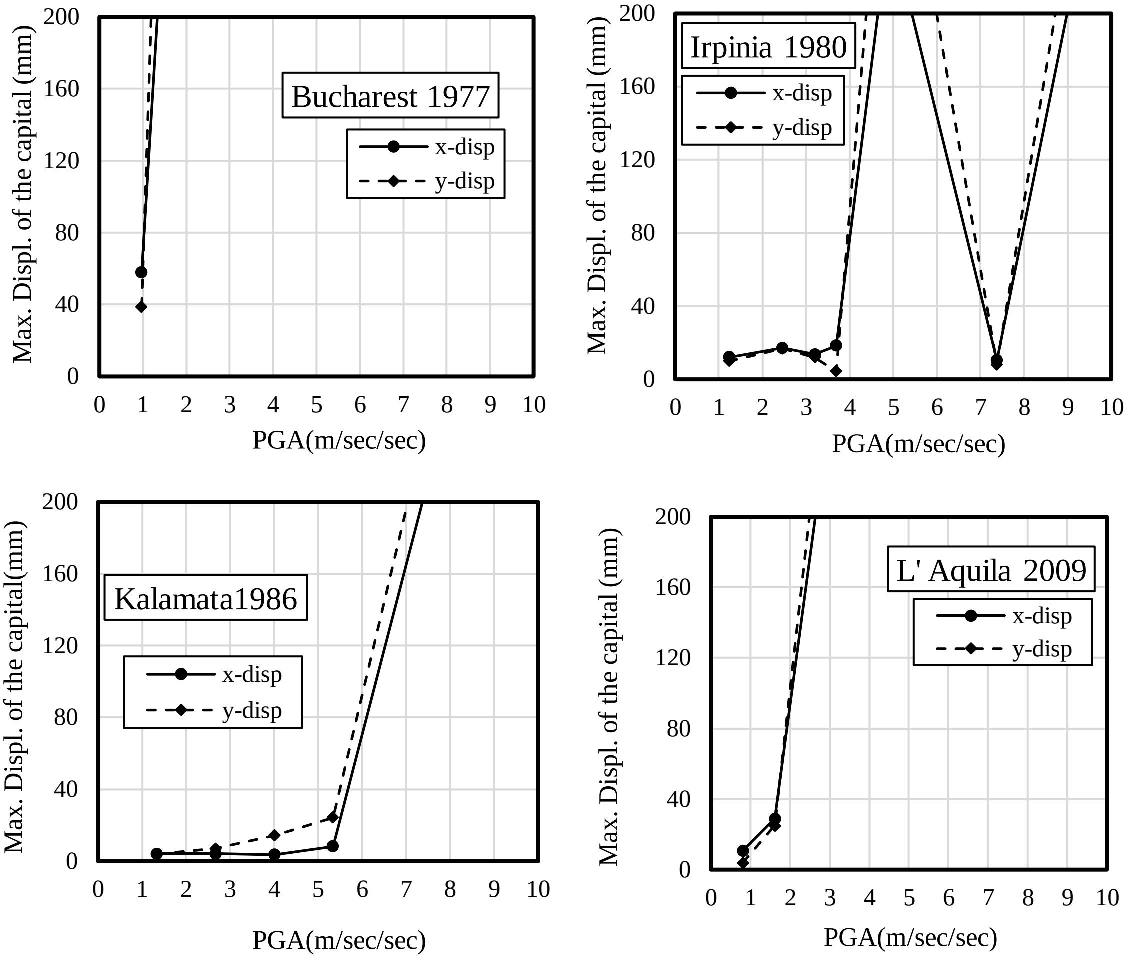


Fig. 14 Maximum displacement of the capital against peak ground acceleration (out-of-plane excitation)

6.2 Effect of solid beam versus segmented beams under in-plane excitations

In Fig. 15, the behavior of the two-storey colonnade with segmented beams is compared with the behavior of the same system with solid beams under in-plane excitations. As can be seen, replacement of segmented beams with solid, may have different effects on the system seismic response depending on the earthquake records characteristics. The system with solid and segmented beams experience almost the same displacements under the Bucharest and Irpinia earthquake records. However, the system with solid beam is more vulnerable than the one with segmented beam under the L'Aquila record, whereas the opposite holds for the Kalamata record.

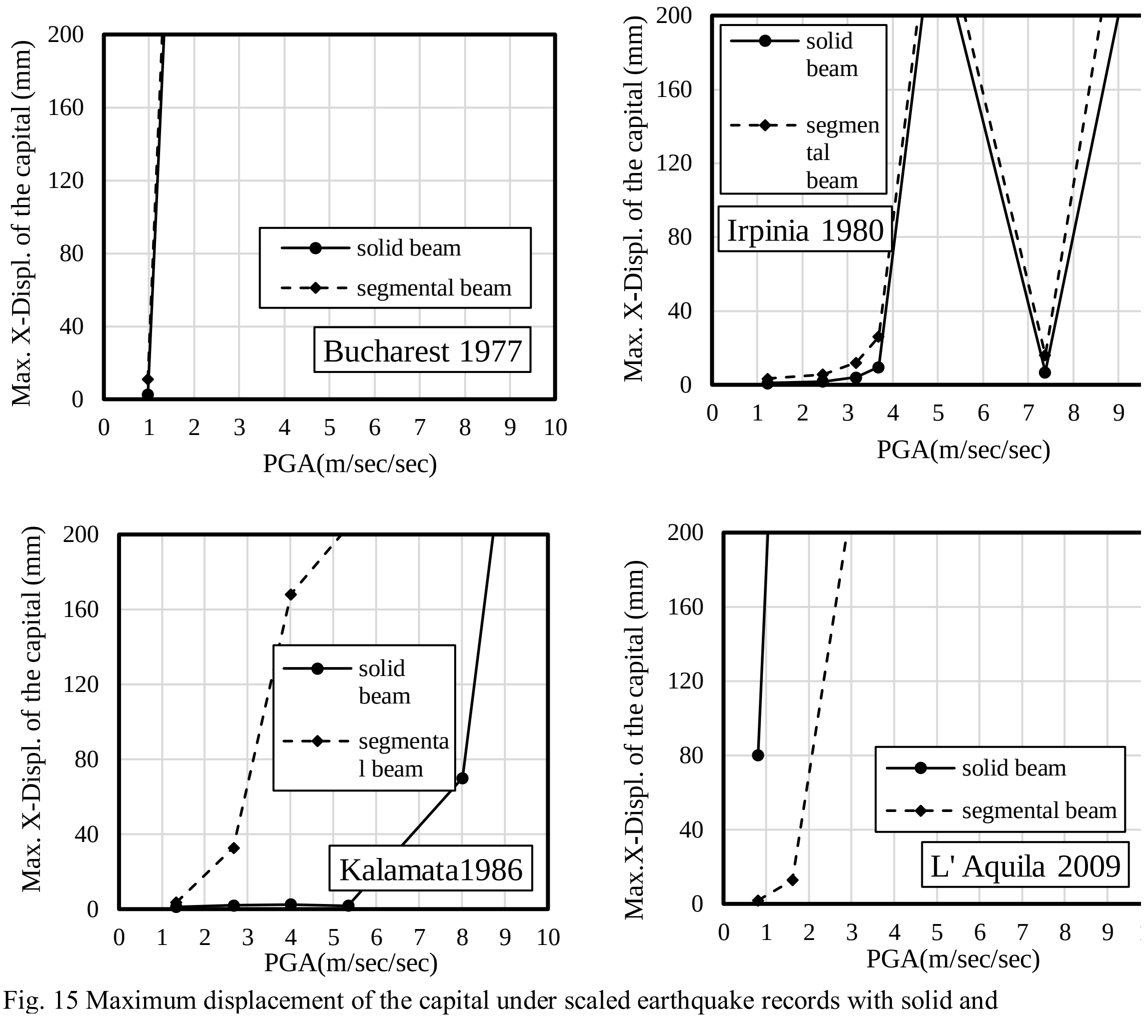


Fig. 15 Maximum displacement of the capital under scaled earthquake records with solid and segmental beams (in-plane excitation)

In Fig. 16, the behavior of the two-storey colonnade with segmented beam is compared with the behavior of the same system with solid beam under out-of-plane plane excitations. Similar to the in-plane excitation results presented in Fig. 15, it is seen that the use of solid beam can alter the system response differently depending on the earthquake records characteristics. The system with solid and segmented beams experience almost the same displacements under the Bucharest, Irpinia and Kalamata earthquake records. However, the system with solid beam is more vulnerable than the one with segmented beam under the L'Aquila record.

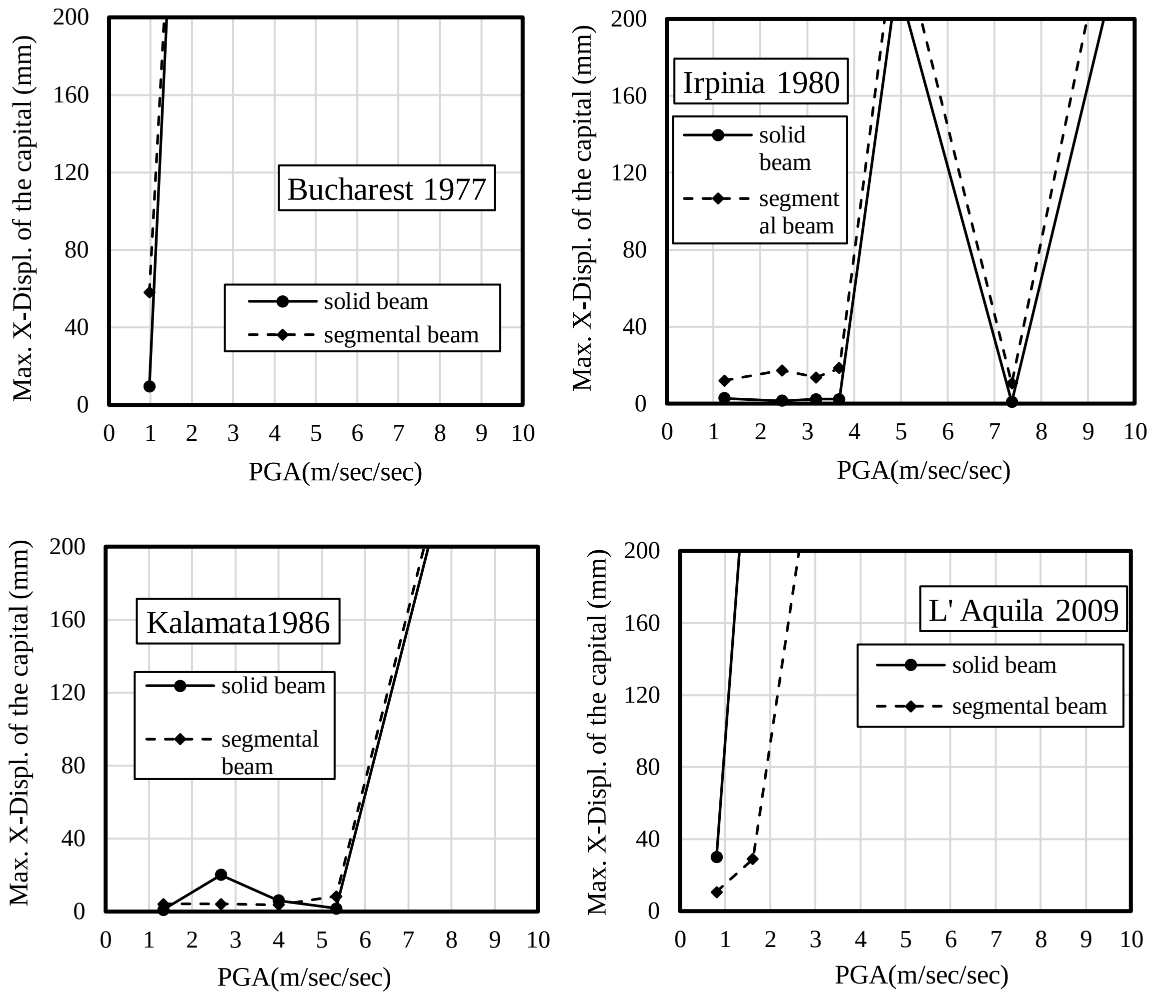


Fig. 16 Maximum displacement of the capital under scaled earthquake records with solid and segmental beams (out-of-plane excitation)

7. Comparison of two against three dimensional analysis

As it was mentioned earlier, a 2D analysis may present greater stability for the seismic response of free-standing monuments in comparison with a 3D analysis. In order to investigate the conservatism of a 2D analysis for the two story colonnade, the results of the 3D analysis performed in this research are compared with the results of a 2D analysis (Sarhosis et al. 2016). In this case, seismic load assigned both in the yy' and xx' directions at the base of the colonnade. Figure 17 shows the results analysis for the studied different seismic loads. From Figure 17 it can be seen that for the 3D analysis, the colonnade at a given PGA generally experiences much more displacement in comparison with the results found in the 2D analysis. This may be attributed to the bidirectional vibration of the system under one dimensional excitations as discussed earlier in Sec. 6.1. Therefore, a 3D simulation approach is more reliable to investigate the real seismic response of the two-storey colonnade.

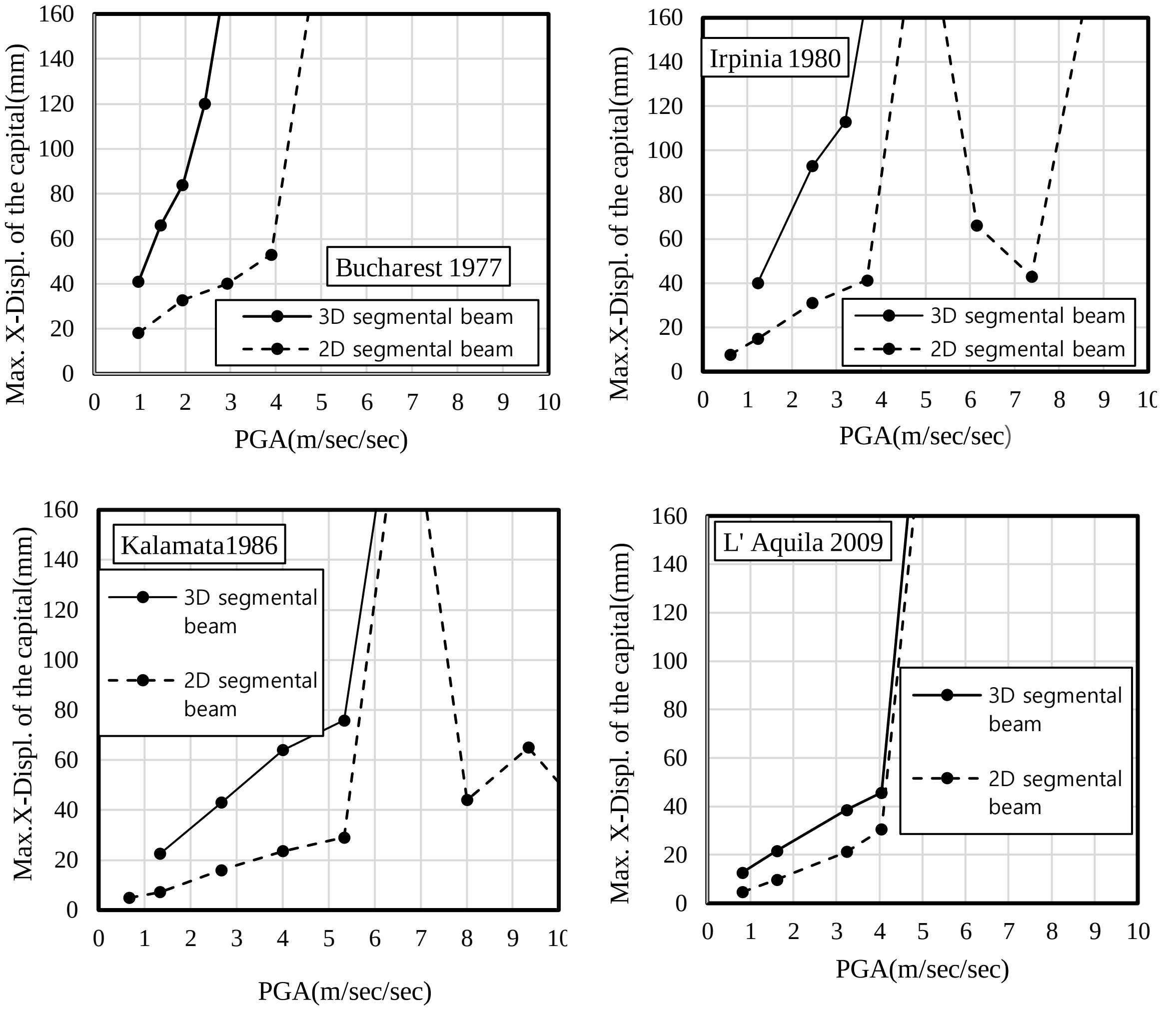


Fig. 17 Comparison of 2D against 3D analysis results for the system with segmental beam (in-plane excitation)

8. Conclusions

This paper aims to investigate the parameters affecting the seismic behaviour of ancient colonnade structural systems. A typical section of the two storey colonnade of the Forum in Pompeii has been modelled and studied parametrically, in order to identify the main factors affecting the stability and to improve our understanding of its behaviour under dynamic loading. A three-dimensional discrete element model was developed using the specialized discrete element software 3DEC (Itasca, 1998) for the dynamic stability analysis of the colonnade. The structure was subjected to harmonic excitation loads with the frequency ranging from 1 to 7 Hz and the amplitude at the base acceleration ranging from 1.7 to 80 m/s^2. This model was also used to compare the results between the 2D and 3D simulations emphasizing the differences for the selected earthquake records.

From the results analysis it was found that low-frequency harmonic excitations are more prominent to cause structural collapse of the two storey colonnade than the high-frequency ones with predominant rocking failure mode.

Also, four earthquake records (Bucharest 1977, Irpinia 1980, Kalamata 1986, L'Aquila 2009) with different characteristics such as the magnitude, the predominant period, the frequency and the type of seismic wave (sinusoidal or not) were used in order to investigate the stability of the two-storey colonnade to various seismic excitations. Apart from the Bucharest 1977 earthquake, during seismic excitations, the maximum out-of-plane and in-plane displacements are of the same order. This means that due to the presence of some eccentricities and applied torsional moments, the colonnade structure vibrates bi-directionally under the in-plane excitations. Also, the colonnade is more vulnerable to the Bucharest and the L'Aquila records under out-of-plane excitation. Therefore, there is a degree of coupling between the in-plane and out-of-plane motions of the colonnade under the out-of-plane excitations.

In addition, the behavior of the two-storey colonnade with segmented beams compared with the behavior of the same system with solid beams under out-of-plane plane excitations. From the analyses, it was found that the use of solid beams can alter the system response differently depending on the earthquake records characteristics. The system with solid and segmented beams experienced almost the same displacements under the Bucharest and Irpinia earthquake records. However, the system with a solid beam was more vulnerable under the L'Aquila record than the one with a segmented beam.

Finally, the model used to compare the results between 2D and 3D simulations emphasized on the different response for the selected earthquake records. From the analysis, the 3D simulation approach is more reliable to investigate the real seismic response of the two-storey colonnade. For the 3D analysis, the colonnade at a given PGA found to sustain higher displacement in comparison with that found in the 2D analysis. This may be attributed to the bi-directional vibration of the system under one dimensional excitations.

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