Investigation of induced seismic forces at joints of classical columns for design purposes

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SUMMARY:
Columns and colonnades of classical monuments are made of assemblies of stone blocks that are connected by means of frictional joints and, in some cases, connectors in the vertical direction (dowels). During the restoration process, missing fragments are usually replaced by new pieces, which are fixed into place with cement mortar and connected to the ancient ones by reinforcement typically made of threaded titanium bars. The design of the reinforcement is based on the capacity concept for the maximum forces that are applied at the joints during the seismic excitation, which are mostly affected by the rocking and sliding of the stone blocks. In this paper, dynamic numerical analyses are performed for three classical columns and six recorded earthquake motions in order to determine the normal and the shear forces that are induced to the joints. Based on the results, values of the coefficient of dynamic amplification of the static forces are proposed for design purposes.

Keywords: restoration; design of connections; classical columns; forces at joints; earthquake response

1. INTRODUCTION

During the restoration of ancient monuments, it is common to complete missing parts of the stones with new complements and to connect broken pieces together in order to restore the integrity of the structure as much as possible. This joining of fragmented pieces is usually made with titanium threaded bars that are inserted in properly drilled holes and fixed into place by mortar. Mortar is also used as the bonding material at the interface of the fraction.

Another type of intervention is the restoration of the connections between the individual structural elements of the monument. It is noted that ancient colonnades consist of stone blocks of different sizes and shapes made of marble, stiff limestone or porous stone, depending on the available material in the nearby region. Typically, the blocks are not connected to each other, except of connectors (clamps and dowels) that are provided in certain places only. In current restoration practice, ancient mortises that are preserved in such places are used to connect the stone blocks with new clamps and dowels made of titanium.

In both types of the above-mentioned restoration procedures, the principle in designing the connectors between the structural elements and the reinforcement that is used for joining together fragments and/or complements is that the titanium elements should bear the induced forces in a seismic event while the marble does not suffer any damage. Therefore, for the proper dimensioning of these elements difficult nonlinear analyses would be required for the determination of the induced forces to them, which would take under consideration the rocking and the sliding of the individual stones. However, such analyses are seldom performed in practice and simplified analyses based on the capacity design concept are performed instead (Zambas 1994, Ioannidou et al. 2000). In such analyses, the vertical forces that apply at the joints are usually increased arbitrarily by a factor of about 1.50 to account for dynamic effects due to the impact between adjacent blocks during rocking, while the horizontal joint forces are put equal to the friction ones, assuming that sliding occurs at the joint. Then, the required reinforcement is calculated from equilibrium conditions of the complement piece considering the capacity actions and the ultimate resistance of any existing dowels.

In this paper, rigorous nonlinear dynamic analyses are performed in order to check the above-mentioned design procedure. More specifically, three case studies were selected and the normal and the tangential (shear) forces induced at the joints between the drums of the columns under six strong earthquake motions with different characteristics were calculated. The selected case studies concern the colonnades of the southern Arcade of the Ancient Agora of Kos, Greece, a column of the Parthenon Pronaos and two columns of the temple of Olympius Zeus (Olympieion) in Athens, connected with an architrave. In this way, monuments with columns of different dimensions were selected, as it is known that the seismic response of monuments is size dependent.

2. DESCRIPTION OF THE MONUMENTS

2.1. Arcade of the Ancient Agora in Kos

The first case study concerned a colonnade which is based on the part of the southern Arcade (Stoa) of the Ancient Agora in the island of Kos, Greece that has been proposed to be restored. Specifically, two columns of the Stoa and the superimposed part of the entablature were considered (Figure 1). The columns are of Doric style bearing fluting at their upper part only, above 2.07 m. Each column consists of four drums of uneven height, with base diameter 0.78 m, top diameter 0.635 m and overall height 5.61 m, the capital of height 0.38 m and the abacus of plan dimensions 0.85 m × 0.85 m and height 0.11 m. The axial distance between the columns is 2.66 m and is spanned with a single block architrave, 2.66 m in length, 0.71 m in width and 0.47 m in height. Upon the architrave, two blocks of the frieze are resting eccentrically, with dimensions 1.73 m (length) × 0.59 m (height) × 0.47 m (overall width). On the upper part, one block of the cornice is placed with length 1.95 m, height 0.42 m and a projecting part of 0.325 m.

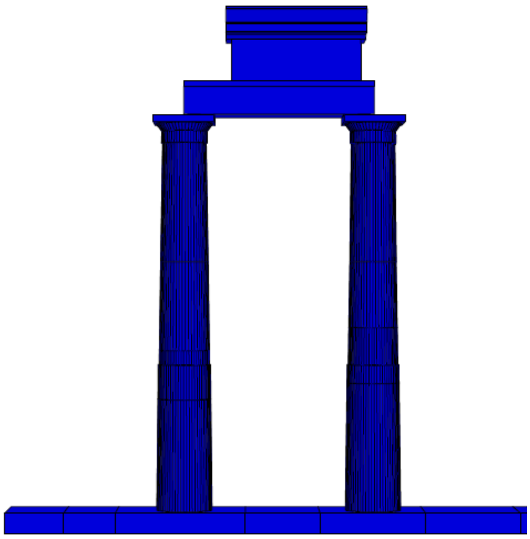
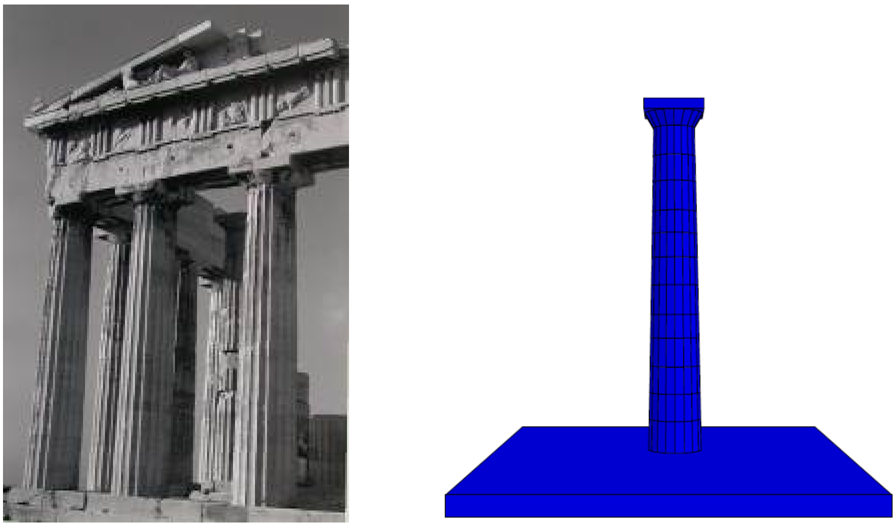


Figure 1. Numerical model of the part of the southern Arcade of the Ancient Agora in Kos used in the analyses.

2.2. Column of the Parthenon Pronaos

The second case study concerned a column of the restored part of the Parthenon's Pronaos (Figure 2), situated in the Acropolis of Athens, Greece (Zambas 1994). The column is of Doric style with fluting and consists of 12 drums of uneven height. The base diameter is 1.65 m, the top diameter 1.25 m and the overall height is 9.39 m. The height of the capital is 0.69 m, while the abacus has plan dimensions 1.65 m × 1.65 m and height 0.35 m.

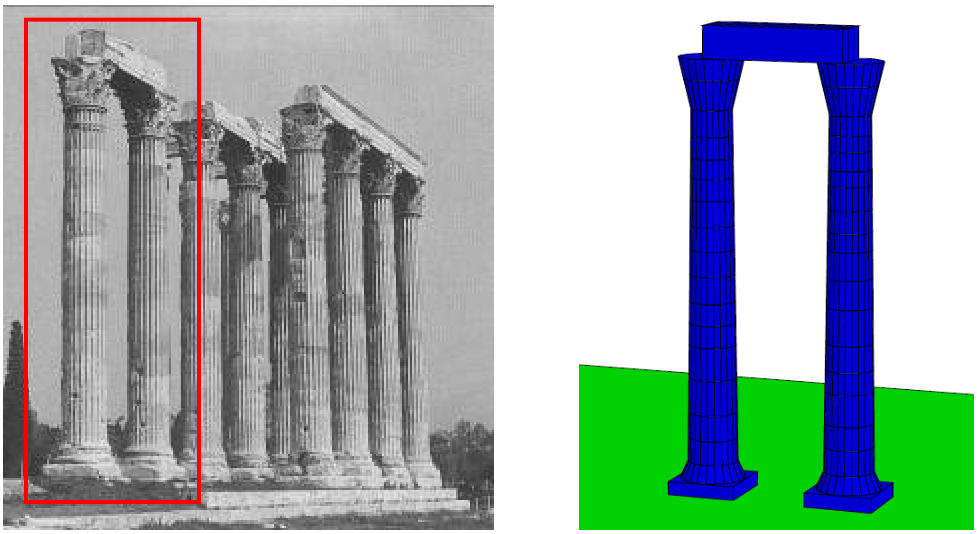


(a) (b)

Figure 2. (a) View of the SE corner of the Parthenon. Behind the columns of the east façade the SE column of the Pronaos can be seen; (b) Numerical model of the column used in the analyses.

2.3. Columns of the Olympieion in Athens

The third case study concerned the two columns connected with an architrave of the SE corner of the temple of Olympios Zeus, known as Olympieion (Figure 3) and situated in Athens, Greece. The capitals are of Corinthian style and the drums of Ionian style with 22 flutes. This monument is significantly larger than the previous ones. The columns have diameter equal to 1.92 m at their base and 1.57 m at their top with an enlarged base of diameter 2.51 m. They sit on plinths of plan dimensions 2.51 m × 2.51 m and height 0.52 m. The drums are of uneven height and number, fourteen in one column and fifteen in the other. The capitals consist of two parts and their height is 1.99 m. The overall height of the columns, including the base and the capital, is 16.81 m and the axial distance between them is 5.50 m. The same is the length of the architrave beams. The architrave consists of three equal beams placed one by the other with total width 1.83 m. In the original structure, two steel dowels, oriented randomly in the directions NS or EW, exist at each joint between drums. These dowels are of square cross-section with an area varying from 9 to 14 cm^2 and a length of 12 to 14 cm (Korres 2002).



(a) (b)

Figure 3. (a) SE corner of the Olympieion in Athens. The considered columns are the ones in the red frame; (b) Numerical model used in the analyses.

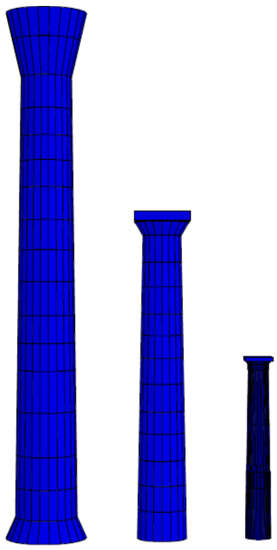
2.4. Comparison of the columns of the monuments

As mentioned above, the dimensions of the monuments are considerably different. This was taken under consideration in selecting the case studies, since it is known that the size of a monument affects significantly its seismic response (Psycharis et al. 2000). The comparison of the geometric properties of the columns is shown in Table 1, while the columns of the three monuments are plotted in the same scale in Figure 4. It is noted that the slenderness of the columns (equal to the ratio of the height over the base diameter) is almost the same for the columns of Pronaos and Olympieion and a little larger for the column of Kos.

Table 1. Comparison of the geometric properties of the columns of the monuments considered.

Monument	Base diameter (m)	Height[1] (m)	Number of drums[2]	Slenderness (H/D)
Kos	0.78	6.11	5	7.83
Pronaos	1.65	10.43	13	6.32
Olympieion	2.51	16.81	17-18	6.70

[1] Including the base, the capital and the abacus.
[2] Including the base and the capital.



(a) (b) (c)

Figure 4. Comparison of the size of the columns of the three monuments considered: (a) Olympieion; (b) Pronaos; (c) Kos.

3. NUMERICAL ANALYSIS

3.1. Numerical model and method of analysis

The dynamic analysis of ancient temples or sub-assemblages of ancient temples differs significantly from the analysis carried out for modern structures, due to their articulate construction. During a seismic event, rocking and/or sliding of the stones, independently or in groups, may occur, which results in highly nonlinear behaviour. Additionally, the response is very sensitive to the details of the geometry, the characteristics of the ground motion and the joint parameters (Psycharis et al. 2000, Papantonopoulos et al. 2002, Psycharis et al. 2003, Dasiou et al. 2009).

The complexity and the special character of the response of such structures (rocking and sliding) create computational requirements hard to meet with the incorporation of conventional software. For the numerical analyses presented herein, the code 3DEC by Itasca Consulting Group, Inc. was employed, which is based on the discrete element method. The code is designed to allow significant displacements and rotations of the blocks, even total detachment. During the calculation process, the code locates the contacts between the blocks and computes the motion of each block from the forces (normal and shear) that are developed at the joints. The contacts are divided in sub-surfaces, while various types of contact are considered (apex to apex, apex to edge etc.). In this way, rocking and sliding are accurately addressed. The code 3DEC has been verified and calibrated for the response of ancient colonnades through comparisons of the numerical results with experimental data obtained from shaking table tests performed at the Laboratory for Earthquake Engineering of the National Technical University of Athens (Papantonopoulos et al. 2002, Dasiou et al. 2009).

The analyses were performed assuming that all the structural elements are rigid blocks, as all the parts of the monuments are made of marble. The joint properties used in the model were based on former studies (Papantonopoulos et al. 2002, Dasiou et al. 2009): the joint stiffness was set equal to 5×10^6 kPa/m in the normal direction and 1×10^6 kPa/m in the tangential direction, while the friction coefficient was taken equal to 0.75. A 10% mass-proportional damping at f = 0.3 Hz was also considered. In the case of Olympieion, the dowels between the drums were modelled as non-linear shear connectors with properties: shear stiffness 5.8×10^5 kN/m and yield force in shear 220 kN. These properties correspond to a 12 cm long dowel with 9 cm^2 cross-section, as in the real structure, made of steel with Young's modulus equal to 2.0×10^8 kPa and ultimate strength in shear equal to 240 MPa.

3.2. Seismic input

The analyses aimed to be representative for typical monuments that can be encountered in several places all over the world. For this reason, the earthquake excitations were selected to cover a wide range of recorded ground motions with different characteristics, not necessarily representative of the specific sites of the considered monuments. Six earthquake records were selected from the strong motion data bases: Cosmos Virtual Center; Pacific Earthquake Engineering Research Center (PEER); European Strong-Motion Database (ESD); National Observatory of Athens; Institute of Technical Seismology and Earthquake Resistant Structures (ITSAK), which had different frequency characteristics. Both horizontal components of each earthquake were applied as the base excitation. The selected earthquakes and their characteristics are shown in Table 2. In Figure 5, the time-histories of the acceleration of the components that were applied in the transverse direction are shown. The response spectra of both horizontal components are presented in Figure 6.

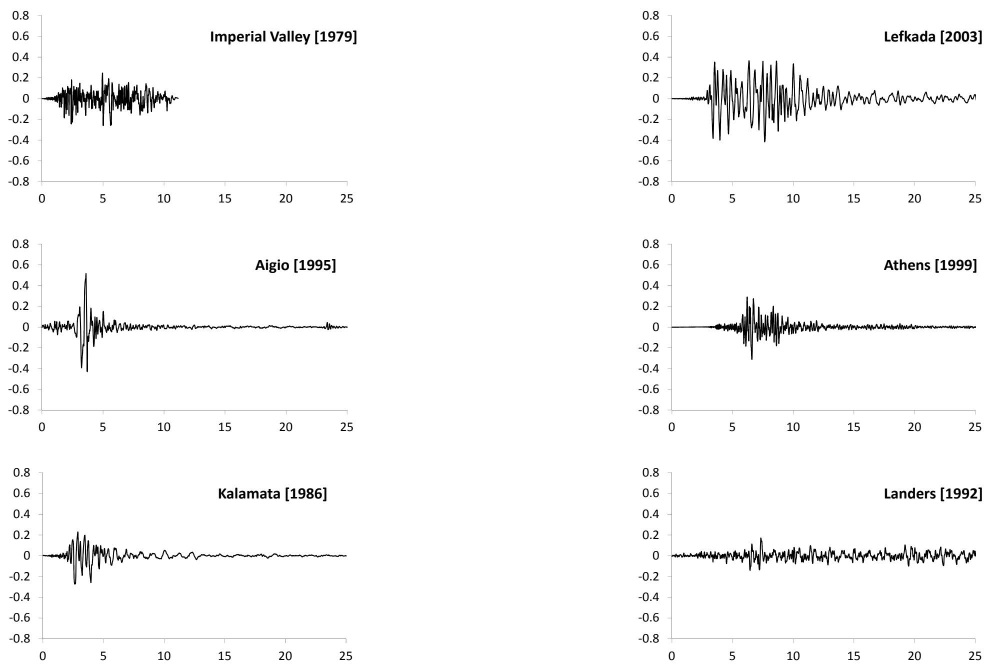
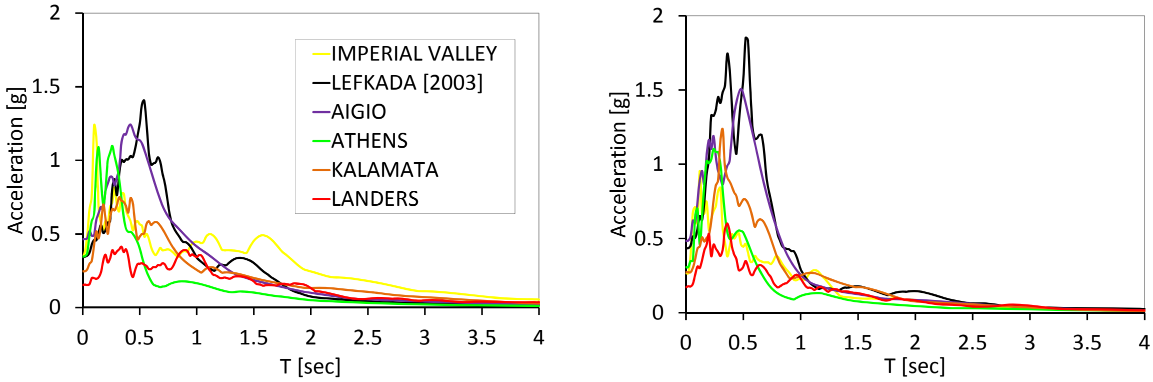


Figure 5. Acceleration time histories of the earthquake records applied in the transverse direction of the monuments.

Table 2. Peak ground accelerations in the two horizontal components of the earthquake records considered.

Earthquake	PGA (g)	
	Longitudinal direction	Transverse direction
Imperial Valley, 1979	0.33	0.25
Lefkada, 2003	0.34	0.42
Aigio, 1995	0.49	0.53
Athens, 1999	0.15	0.23
Kalamata, 1986	0.24	0.27
Landers, 1992	0.15	0.17



(a) (b)

Figure 6. Acceleration response spectra for 5% damping of the horizontal components of the base motions that were applied in: (a) the longitudinal direction and (b) the transverse direction of the monuments**.**

3.3. Results

For each monument and for all earthquake excitations examined, the time histories of the forces that were induced at the joints of the columns were determined. Indicative results are presented in Figures 7-12. All forces are presented normalized with respect to the gravity load of the superstructure, which is applied at the corresponding joint. In this way, the plots of the normalized normal forces, $N_{\mathrm{EQ}}/N_{\mathrm{GRAVITY}}$, show the dynamic amplification of the vertical loads during the earthquake response, while the plots of the normalized shear forces, $S_{\mathrm{EQ}}/N_{\mathrm{Gravity}}$, show whether friction sliding occurred or not. It is reminded that the friction coefficient was considered equal to 0.75, thus it is required that $S_{\mathrm{EQ}}/N_{\mathrm{Gravity}} > 0.75$ in order sliding to start. In the results, a low-pass filtered of 15 Hz was applied to cut-off high frequency peaks.

Figure 7 shows the time histories of the normalized forces that were induced at all joints of column 1 of the colonnade in Kos during the Lefkada earthquake. It is seen that, except of isolated peaks which might have been caused by numerical instabilities, the maximum normal forces (left column) were generally less than 1.5 times the vertical load, while the normalized shear forces were less than 0.45, i.e. considerably less than the friction coefficient.

The normalized normal forces that were induced at the lower joint 1, between the bottom drum and the one above it, for all earthquake motions considered are shown in Figure 8. Again, $N_{\mathrm{EQ}}/N_{\mathrm{GRAVITY}}$ is generally less than 1.5, except of isolated peaks.

Similar results were obtained for the other monuments too. For example, Figure 9 shows the normalized normal forces that were induced at all joints of the column of the Parthenon Pronaos during the Aigio earthquake, while in Figure 10, the normalized normal and shear forces induced at the highest joint 12 are shown for all the earthquake excitations. The corresponding plot for the lowest and highest joint of column 1 of the Olympieion is depicted in Figures 11 and 12 respectively.

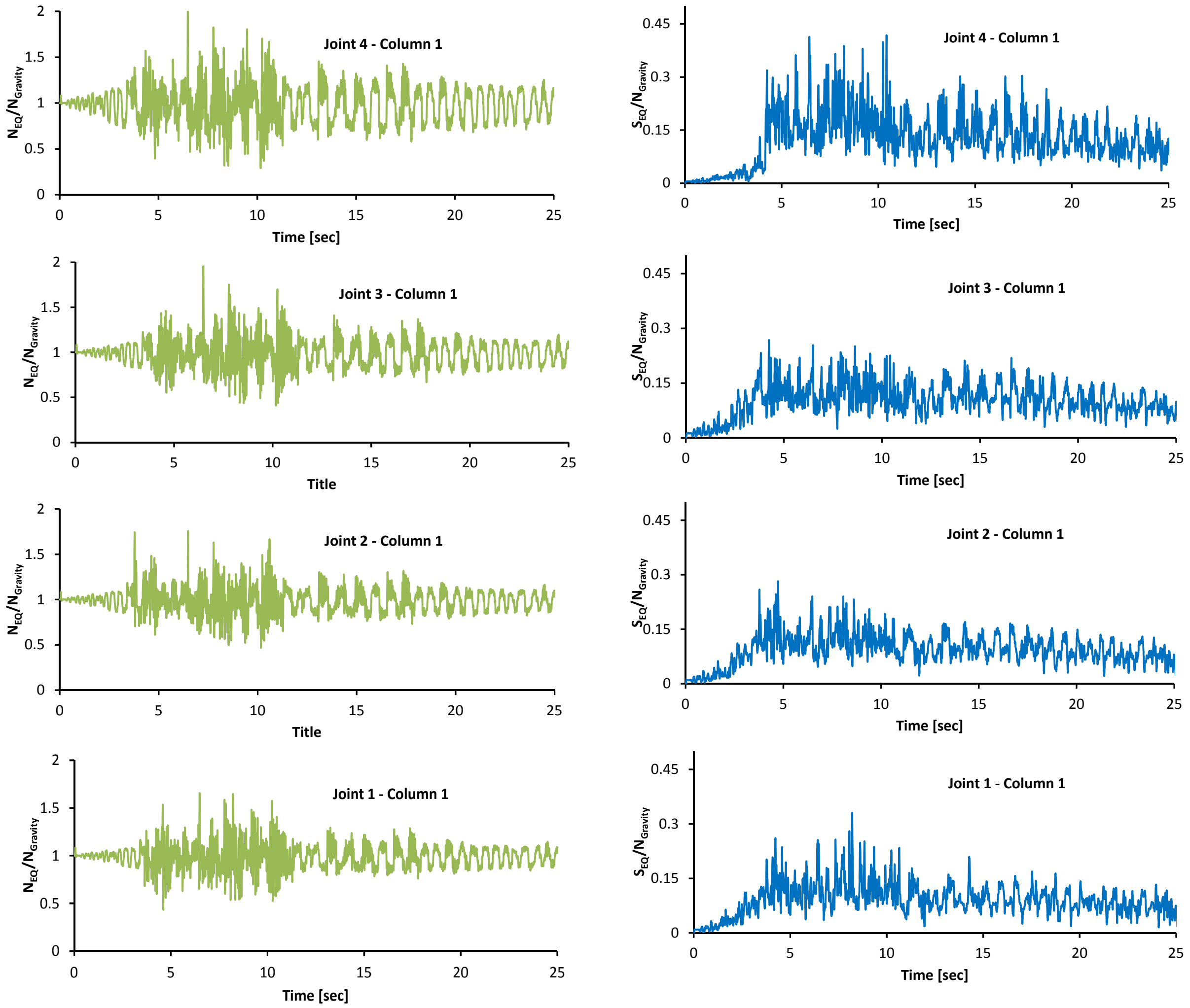


Figure 7. Time histories of the normalized normal (left column) and shear (right column) forces induced at the joints of column 1 of the colonnade in Kos during the Lefkada Earthquake.

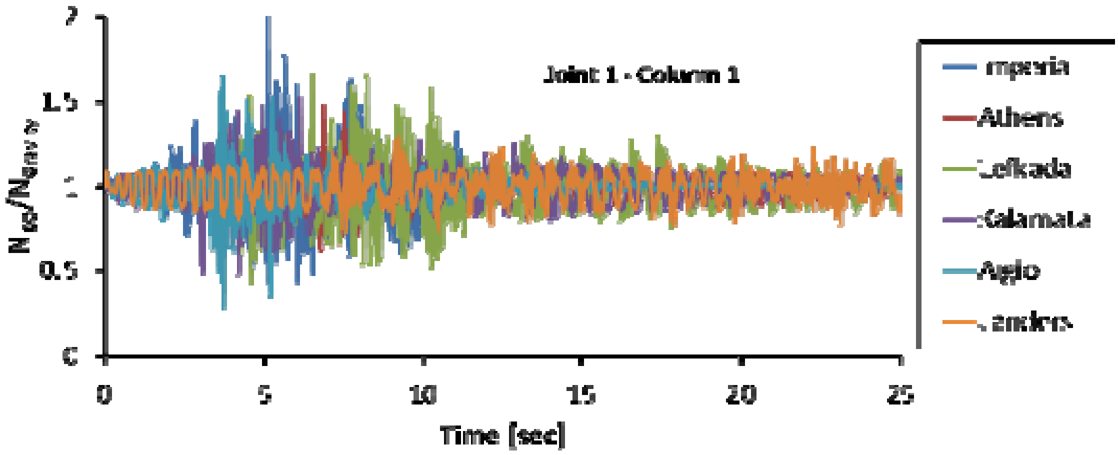


Figure 8. Time histories of the normalized normal forces induced at the lower joint 1 of column 1 of the colonnade in Kos for all earthquake motions considered.

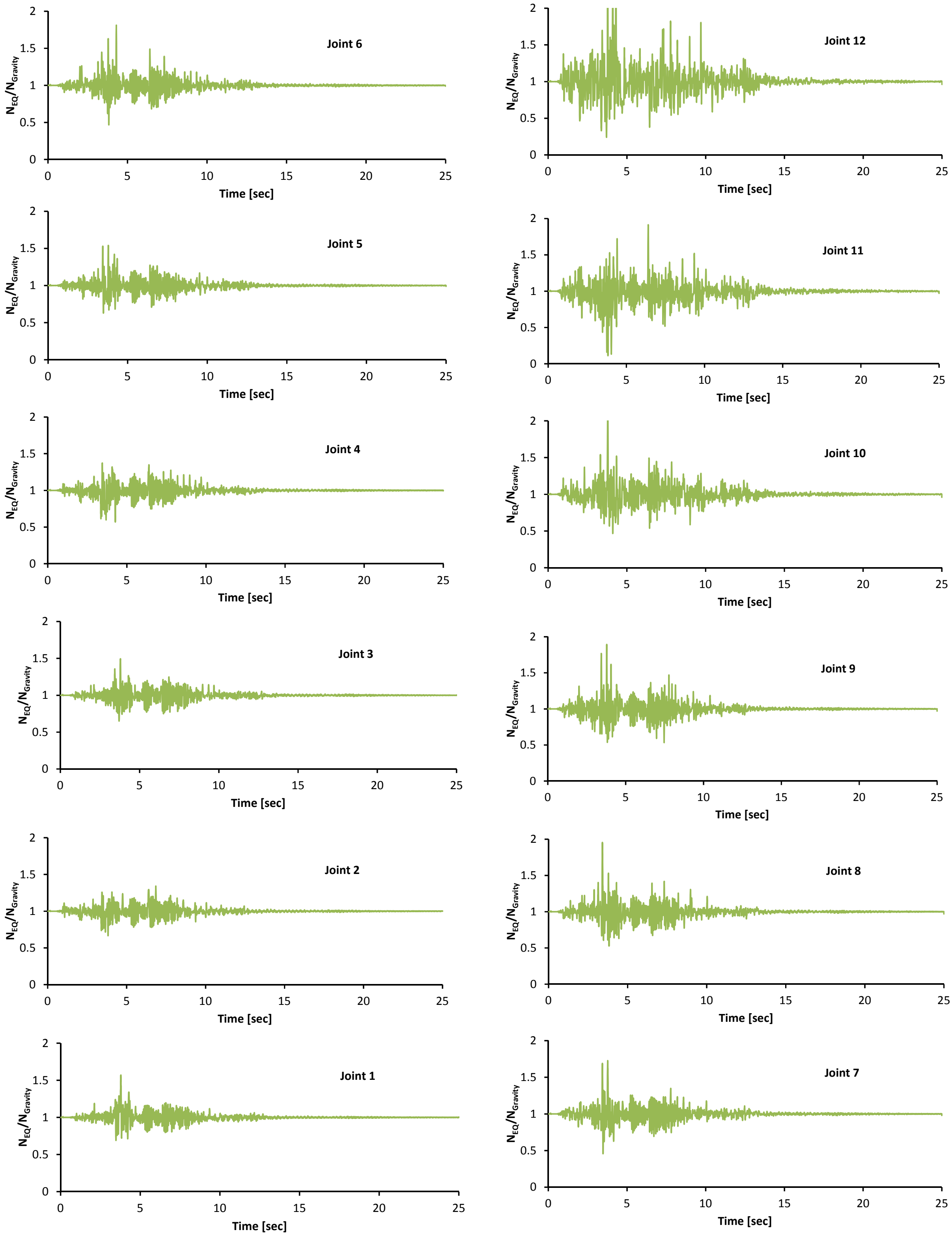


Figure 9. Time histories of the normalized normal forces induced at the joints of the column of the Parthenon Pronaos during the Aigio Earthquake**.**

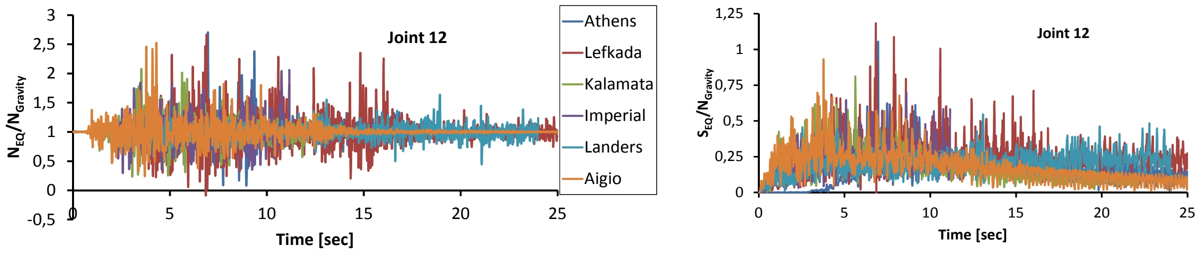


Figure 10. Time histories of the normalized normal and shear forces induced at the highest joint 12 of the column of the Parthenon Pronaos for all earthquake motions considered.

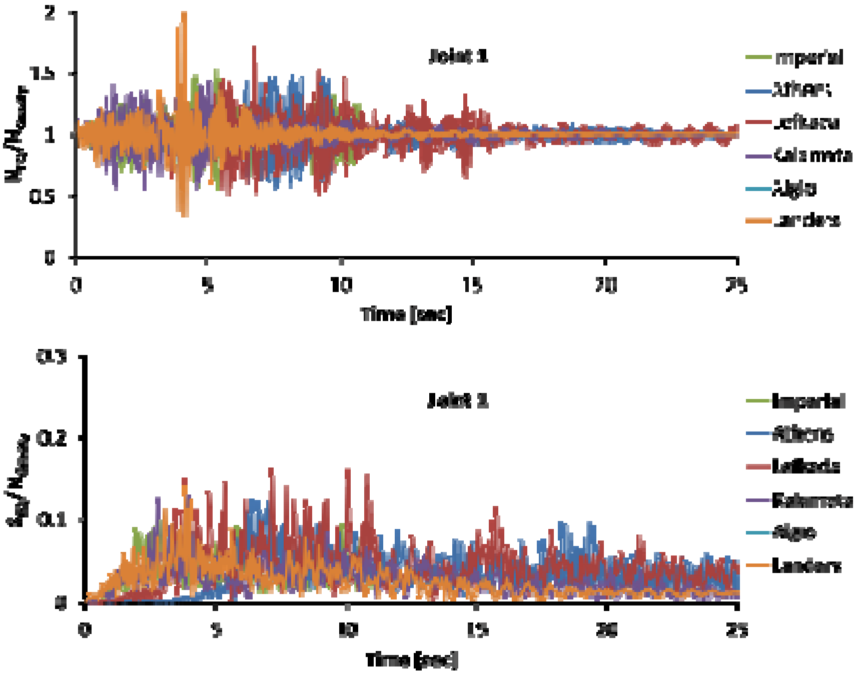


Figure 11. Time histories of the normalized normal and shear forces induced at the lower joint 1 of column 1 of the Olympeion for all earthquake motions considered.

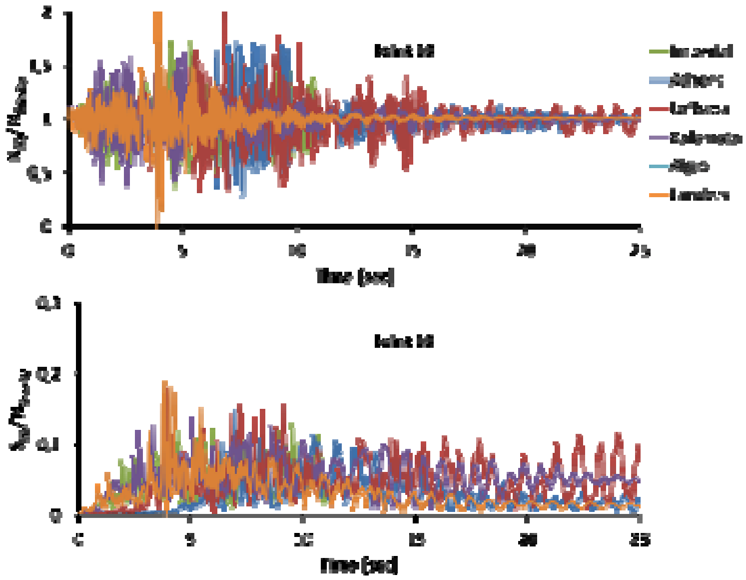


Figure 12. Time histories of the normalized normal and shear forces induced at the highest joint 12 of column 1 of the Olympeion for all earthquake motions considered.

5. CONCLUSIONS AND DESIGN RECOMMENDATIONS

The numerical analyses performed for three significantly different in size monuments and for six earthquake motions with different characteristics showed that:

(a) The normal forces that were induced at the joints between the drums of the columns during the intense shaking were, in general, 1.2 to 1.8 times the corresponding vertical loads due to gravity. Larger forces can be induced during rocking, especially in the upper drums, but they correspond to isolated peaks with small duration, thus they can be neglected for design purposes.
(b) The shear forces that were induced at the joints were, in general, smaller than the ones required to overcome the resistance in friction, especially at the lower joints. It must be noted, however, that friction sliding was observed in some cases at the upper joints of the columns where large horizontal accelerations are developed. Thus, it was not possible to draw solid conclusions from the limited number of analyses performed and more investigation is required on this subject.

Based on these conclusions, it is suggested that, in a capacity design for the dimensioning of the reinforcement of complements to drums and of the connectors between them, the vertical loads must be calculated by applying a dynamic amplification factor in the order of 1.50 to the gravity load of the superstructure. The horizontal shear capacity force that must be considered at the joints can be smaller than friction for the lower drums and equal to the corresponding friction for the upper part of the column.

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