SEISMIC RESPONSE OF THE COLUMNS OF TWO ANCIENT GREEK TEMPLES IN RHODES AND LINDOS

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ABSTRACT

The paper presents a numerical study of the seismic response of multidrum and monolithic columns of ancient Greek temples. Due to the highly non-linear behavior of these structures, an analytical approach is practically impossible and the use of numerical methods is necessary. The structures were modeled using a commercial 3D finite element model, (ANSYS v.11.0). The behavior of the interfaces between drums is modeled with contact friction element. The aim of the paper is to investigate the "chaotic" response of these complex structures and to evaluate the critical acceleration of column's collapse, through appropriate parametric analyses. Several selected seismic input motions, presenting different amplitudes and frequency content were used, properly scaled (Aigion 1995, Erzincan 1992, Friuli 1976, Kozani 1995). Rocking, sliding and combined behavior of two monolithic columns, having the same overall geometric and material characteristics of the actual columns were also examined. Finally, in order to examine the possible effects of inappropriate past restoration practices and the degradation of limestone properties with aging, we examined the effects of reduced elasticity values corresponding to different levels of deterioration of the local limestone used in the reconstruction, as well as reduction of the dynamic coefficient of friction at the contact surfaces.

INTRODUCTION

Ancient Roman and Greek temples are distinctly different from modern flexible structures. Ancient temples consist of multidrum or monolithic columns (colonnades), connected at the top with entablature. Gravity and horizontal temporary loads were carried to the ground by means of monolithic and multidrum columns. The columns composed of large blocks (drums) of marble or limestone with no connecting mortar. Wooden or bronze bins (like shear keys) called "polos" and "empolio" are often used between drums to achieve perfect contact between them without increasing the interface shear resistance beyond a certain level. The drums are left free to rock and slide during the seismic excitation when certain level of intensity is exceeded. In fact, this construction practice of finite strength that does not exceed the compressive strength of the drums could be seen as an early version of the capacity design process that is currently used for the seismic protection of structures.

These systems have received recently increasing scientific attention due to their "chaotic" behavior. Their seismic response is controlled by rocking and sliding mechanisms, or the combination of these two. During an earthquake, the drums can slide and/or rock independently, and dissipate significant amount of energy through inelastic response and differential displacements. It is a multi-parametric problem involving both material and geometrical non-linearities. The column response may go through several modes during the seismic excitation, with no specific modes with their classical meaning in continuum. The columns response depends on the 'polos' shear strength, the evolution of the friction at the interface between the drums, which is not uniform, the ultimate shear strength of the interface, and the dimension of the drums.

Considering that there is no accurate analytical solution for the analysis of monolithic or multidrum columns, with the exception of few experimental works, almost all-recent research work is based on numerical simulations. ([2]-[4], [7]-[12]). They have been applied in order to understand the physics of the response, to study restoration practices, to check the stability of existing columns and to evaluate the seismic intensity of past earthquakes produced specific damages' patterns to ancient temple columns, through parametric back analysis.

The paper presents a numerical FE study of the seismic response of multidrum and monolithic columns of two ancient Greek temples: the Hellenistic portico of Lindos acropolis and the temple of Apollo in Rhodes (Fig. 1). It should be emphasized that the numerical modeling of the detailed geometric conditions of the ancient columns is practically impossible, while it is known that the effects of the existing "anomalies", especially at the perimeter is extremely difficult to simulate the exact geometry of each interface between the drums; thus, any attempt to study such a case with numerical or even experimental approaches, remains an approximation, however, these methods are always useful in order to estimate response even a qualitative way. The columns are considered being restored with local limestone and parametric analyses were performed in order to examine the behavior of the two examined columns, subjected to seismic motions having different amplitudes and frequency content: Aigio 1995, Erzincan 1992, Friuli 1976, Kozani 1995.

The aim of these parametric studies is to investigate the detailed response of the selected monuments in terms of displacements (absolute and relative), accelerations and stresses time histories at different levels, in the different drums of multidrum and along the monolithic columns, as well as at the contact elements. In addition, we made an effort to determine the level of the threshold ground acceleration, which the restored multidrum columns of Apollo Temple, can survive.

The same columns considered this time as monolithic structures and have been subjected to sinusoidal motion, with gradually increased amplitudes, to investigate the threshold between rocking and sliding of monolithic columns, having the geometrical and material characteristics of the restored columns of Apollo Temple. Finally, in order to examine the possible effects of poor past restoration practices and the degradation of limestone properties with aging and unfavorable environmental conditions, we examined the influence of reduced Young modules corresponding to different levels of deterioration of the local limestone used for the reconstruction, and reduction of the dynamic coefficient of friction at the contact surfaces.

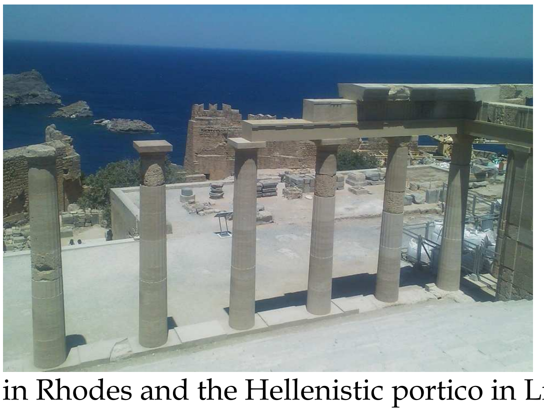



Figure 1: Temple of Apollo in Rhodes and the Hellenistic portico in Lindos.

NUMERICAL MODELING

Geometrical-material data[1]

The multidrum column of the Hellenistic Portico at Lindos Acropolis is 5.0 m high and is composed of seven 0.68m high drums and a capital. The diameters of the drums range from 0.78m at the base to 0.62m at the top. The column of the temple of Apollo is 11.0m high and is composed of eleven 1.0m high drums and a capital. The diameter at the base is 1.77m and at the top 1.40m.

[1] The geometrical data about the multidrum columns of the temple of Apollo was taken by the KB' E.P.K.A, Ministry of Culture (Georgios P. Antoniou)

The same columns considered as monolithic structures, have been studied without the same overall dimensions. Both columns have the same slenderness ratio, B/R≈0.15. In this study the drums are considered simply lie on top of each other in a perfect fit through a contact interface element, without any 'polos-empolio' system. The columns are considered being restored with local limestone having modulus of elasticity E=1044MPa [5], Poisson ratio v=0.25 and density of 2ton/m^3. In order to examine the possible effects of poor past restoration practices and the degradation of limestone properties with aging, we examined the influence of reduced Young modules and dynamic friction values, with appropriate value for each particular case.

Modeling
Contrary to other efforts where discrete element models have been used [12] in our study all analyses were conducted with finite element modeling, using ANSYS v.11.0. The drums are considered here as "deformable blocks", super-posed one to the other through the contact elements. During a strong earthquake with strong reverse pulses, this configuration can generate important absorption mechanism, leading to very complex response. The contact elements were used to simulate the interfaces between the drums, for both sliding and rocking. Their mechanical behavior is governed by friction adopting Mohr Coulomb criterion with zero cohesion and dynamic friction coefficient equal to the static one (i.e. 0.7). Contact elements may also model the rocking effect introducing an appropriate loss of contact. Zero damping was set in all analyses conforming to experimental tests of drum columns which have shown very small attenuation during the seismic motion [8]. However damping may have a more significant effect after the end of driving seismic excitation. The time step for the numerical integration was 10^{-3}s. A larger value led to numerical instabilities (extremely large displacements or overlap between bodies). It was verified that the spatial discretization step affected only the computing cost and not the accuracy of the results. The numerical analysis consisted of two stages. In the first one, the models were subjected to the acceleration of gravity. This allows the weight of the system to be smoothly applied on the model, imposing the friction forces at each contact element. Then the models were subjected to the selected input seismic signals at their base.

Seismic input motions
Four earthquake records with different frequency and amplitude characteristic were selected. The Aigion, Greece 1995, record with PGA approximately equal to 0.5g, was recorded 15km from the epicenter in stiff soil conditions; a strong 0.5sec period pulse dominates it. The Kozani, Greece, 1995, earthquake, with PGA=0.20g (To=0.2-0.3 sec) was recorder in stiff soil conditions, 17km from the epicenter. The Friuli, Italy, 1976 record (PGA = 0.29g) and was recorded at 27km from the epicenter. The last record with PGA=0.41g, was obtained during the Erzincan 1992, earthquake in Turkey, 13km from the epicenter.
The threshold value of PGA that would make the Apollo temple column to collapse, has been evaluated through a parametric study and the column subjected to increasing levels of horizontal acceleration from 0.4g to 1g.

SEISMIC RESPONSE

Displacements
The seismic response of the ancient columns is controlled by rocking and sliding mechanisms, or the combination of these two. During an earthquake, the drums can slide and/or rock independently, and dissipate significant amount of energy through inelastic response and differential displacements. Important out-of-plane displacements are often observed especially in the upper part of the columns. Moreover the capital presents a twisting rotation during the first seconds of excitation even for small values of PGA.

Relative and absolute displacements are larger at the higher drums and especially at the capital. In figure 2 we present the relative in plane and out of plane displacements, between successive drums of the multidrum column K22 of Hellenistic portico, when the Kozani,1995 record with PGA=0.5g is applied at the base. The maximum in-plane relative displacement between the first drum and the base is 3mm, while the maximum displacement between 7th drum and the capital is 2.5cm. The permanent relative displacements between successive drums are smaller than the maximum ones. The most interesting observation is that while higher PGA values leads to larger displacements, the column and the capital do not collapse.

Typical images, at selected time windows, of the seismic response of the two multidrum columns studied in this paper are present in figure 3. We also observe that the columns of Hellenistic portico present larger displacements than the column of the temple of Apollo, which is considerably higher and bigger. The important weight of the drums does not allow them to slide and rock.

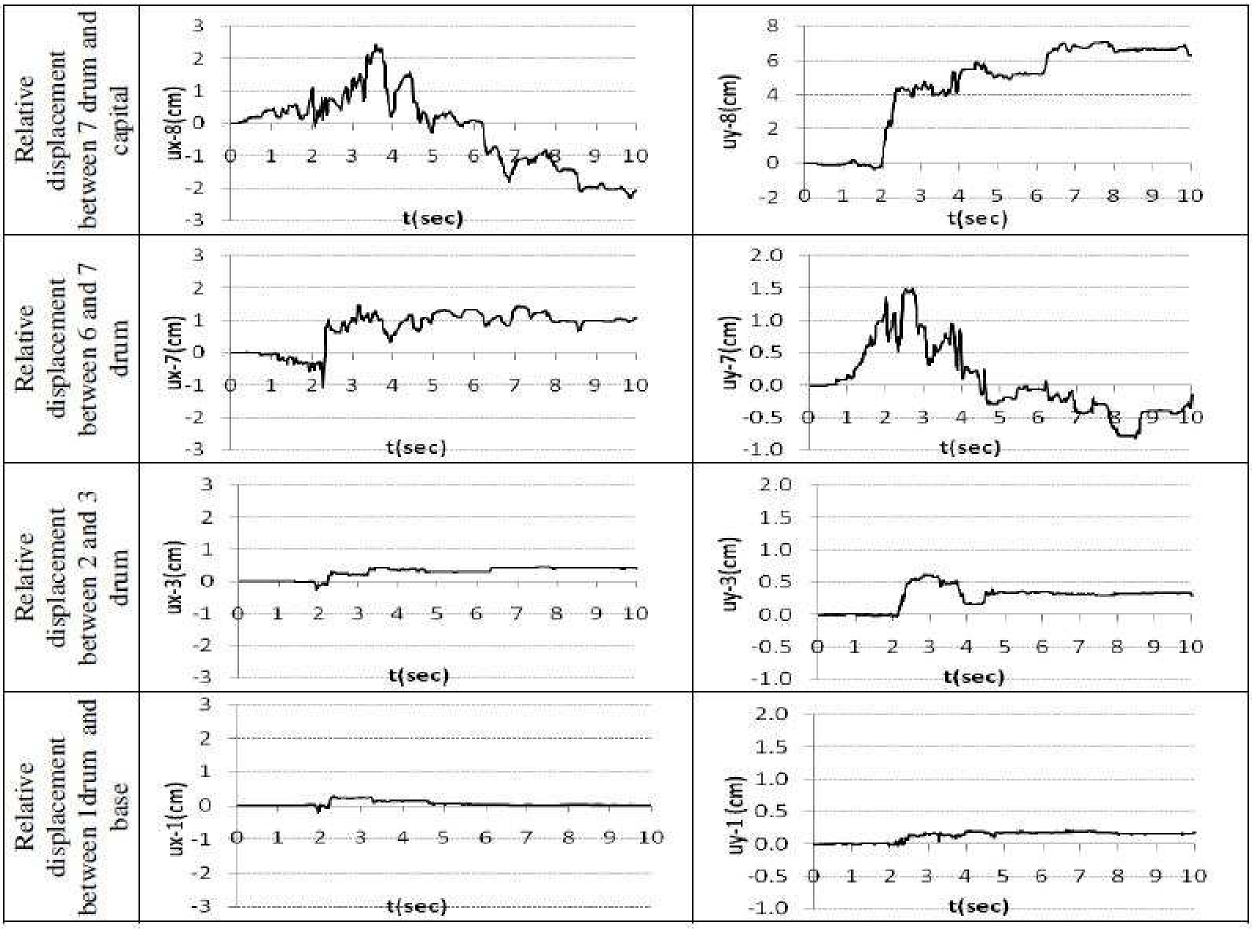


Figure 2: Time histories of in plane and out of plane relative displacements, between drums. Earthquake: Kozani (1995) with PGA=0.5g, Model: multidrum column K22 of Hellenistic portico.

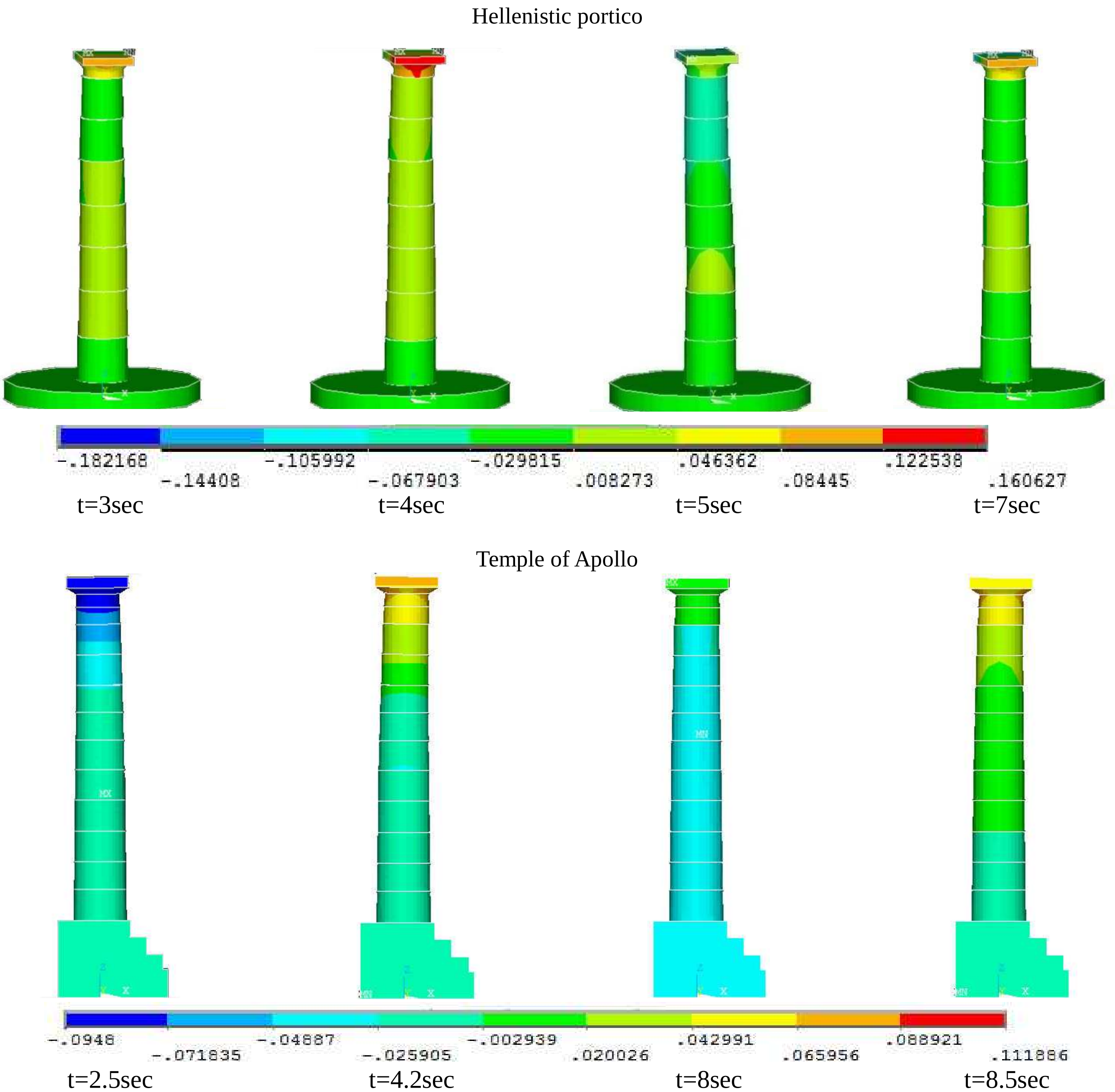


Figure 3: Typical seismic response images, at selected time windows, of the multidrum columns of the Temple of Apollo in Rhodes (down) and the Hellenistic portico in Lindos (up) subjected to the Kozani (1995) earthquake with PGA=0.5g. Absolute displacements in m.

Shearing stresses

The sliding is controlled by the Mohr Coulomb criterion with zero cohesion. The dynamic coefficient of friction is taken equal to the static one (=0.70). Normal and shearing stresses are not constant at the contact interfaces; they continuously altered and varying during the seismic excitation. As soon as the developing shearing stress at an interface will exceed the shear resistance, the drum slides. Figure 4 illustrates the time histories of the developed shear stresses and resistance at a particular point at the upper area of 5th drum of the multidum column K22 of Helleinistic portico, when the record of the Kozani, 1995 earthquake with PGA=0.5g is applied at the base. Shear stresses are remaining always lower than shear resistance.

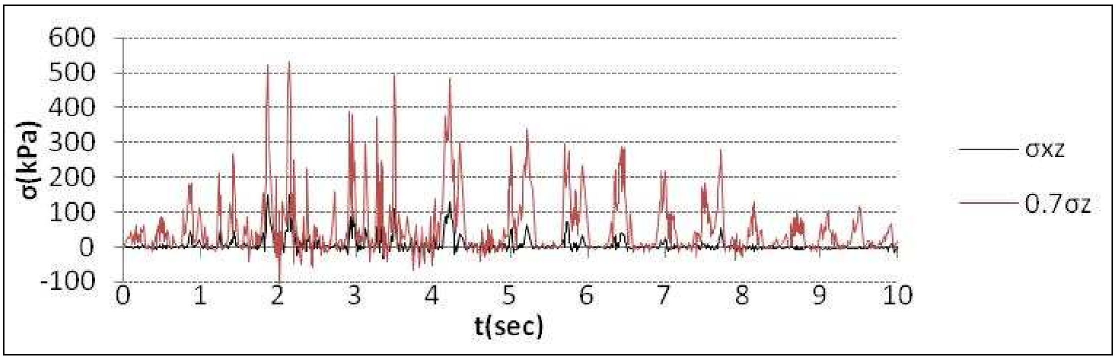


Figure 4: Developed shear stresses time histories and resistance at upper area of 5th drum. Earthquake: Kozani (1995) with PGA=0.5g, Model: multidum column K22 of Hellinistic portico.

Figure 5 presents typical seismic response images, at selected time windows, at the upper surface of 5th drum of the multidrum columns of the Temple of Apollo in Rhodes, for the Erzincan (1992) input motion with PGA=0.5g. Concentrations of shear stresses at the interfaces are observed in particular time steps which are usually occurring when the drum is rocking.

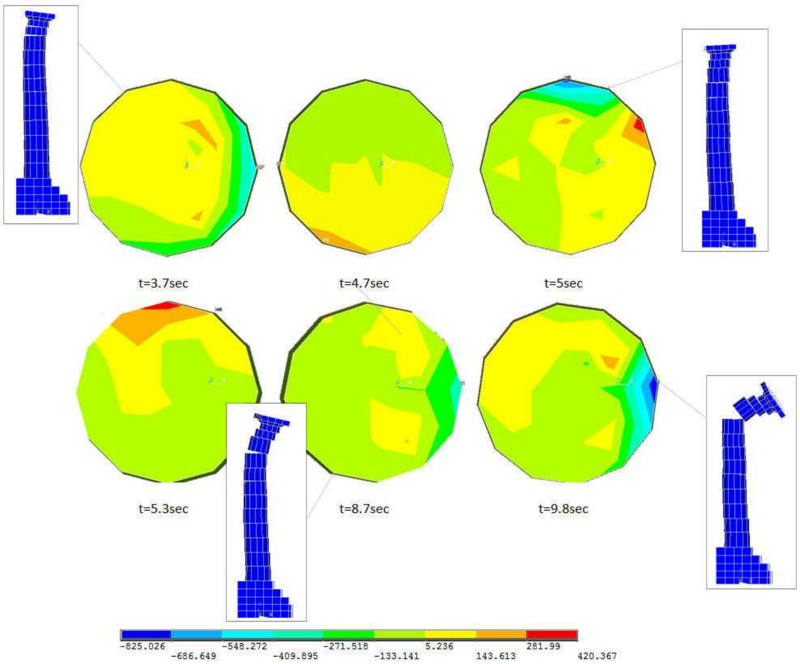


Figure 5: Images of shear stresses, at selected time windows, at upper interface of 5th drum. Erzincan (1992) with PGA=0.5g, Temple of Apollo, column K1,.

Transfer function

The transfer functions illustrated in figure 6 prove that the response of multidrum ancient columns have no modal response. These structures may go through several modes during the same excitation, thus no specific modes exist with the classical meaning and no distinguished dominant period may be identified. As a matter of fact, the modes of such systems depend on the kind of contact existing between the interfaces of adjusting drums. In addition, significant amplification is observed from the base to the top of the column, which is higher in a multidrum column than monolithic one.

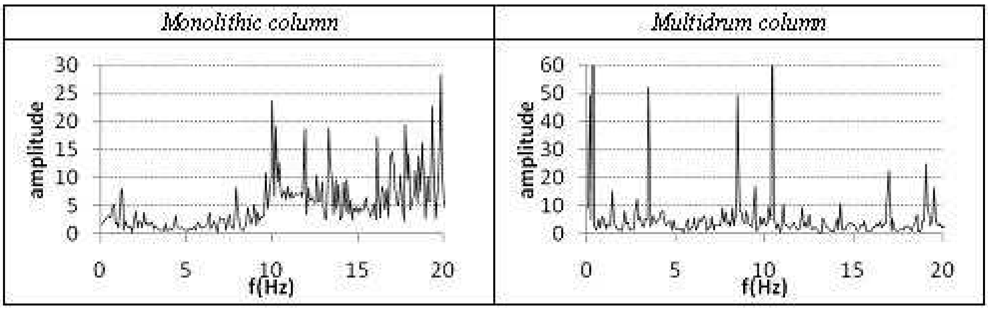


Figure 6: Transfer function from the base to the top of monolithic and multidrum columns of the Hellenistic portico in Lindos. Earthquake: Kozani (1995) with PGA=0.5g.

THRESHOLD BETWEEN ROCKING AND SLIDING OF MONOLITHIC COLUMNS

Pure sliding and rocking, as well as a slide-rock mode control the response of an ancient column. Considering, for simplicity, a monolithic column with the same geometry of the multidrum column we performed parametric analyses subjected to a simple sinusoidal motion (T=1sec), with gradually increased PGA amplitudes varying from 0.2g to 1.0g. The aim is to investigate the threshold between rocking and sliding of the monolithic column, having the same geometric and material characteristics of the column K1 of Apollo temple.

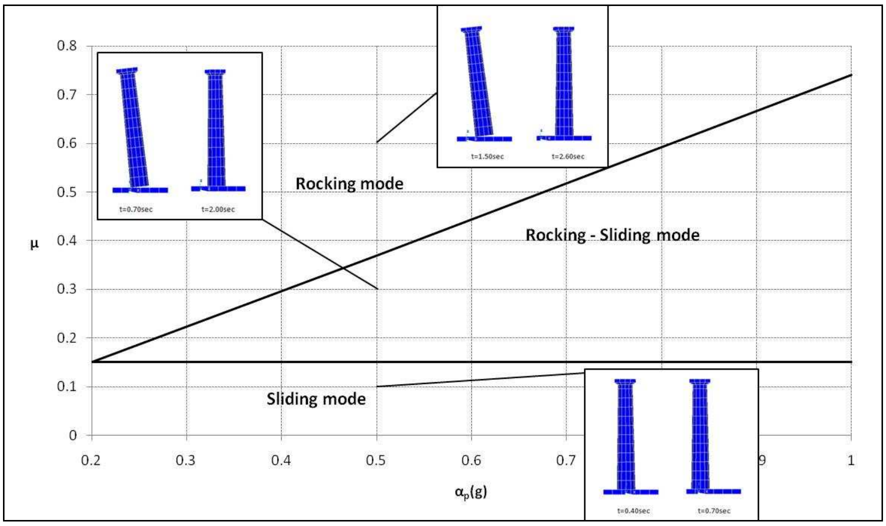


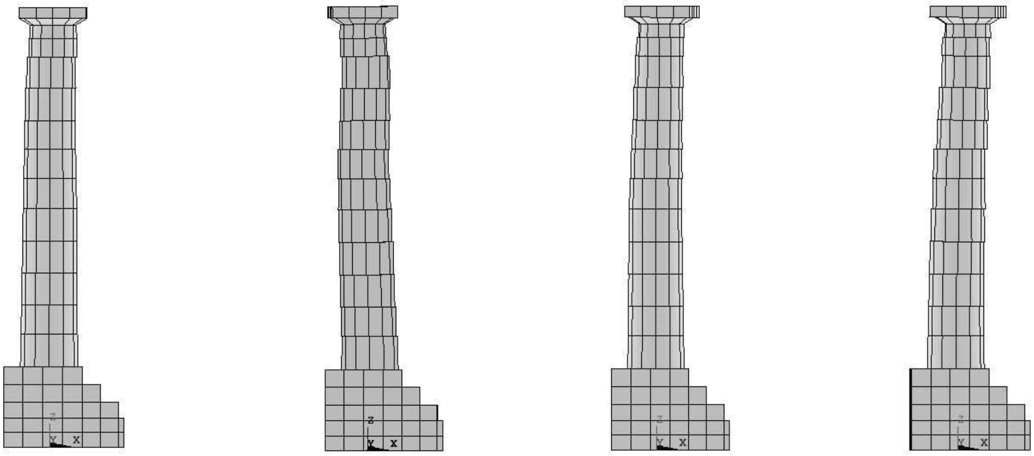
Figure 7: Threshold between sliding, rocking and slide-rocking mode for monolithic column with the same geometrical and material characteristic of the multidrum column of the Temple of Apollo in Rhodes (D/H=0.15).

In figure 7 we present the threshold between sliding, rocking and slide-rocking modes. The results are in agreement with analytical solution for rigid bodies [13] and with similar numerical study for the monolithic column of the Hellenistic portico in Lindos [2]. When the dynamic coefficient of friction is smaller than 0.15 (D/H=0.15), the column's response is controlled by the sliding mode, independently of the value of acceleration. For high values of dynamic coefficient of friction, the monolithic column response is controlled by the rocking mode. There is an intermediate zone of friction coefficients and slenderness ratio where the motion is controlled by both sliding and rocking modes.

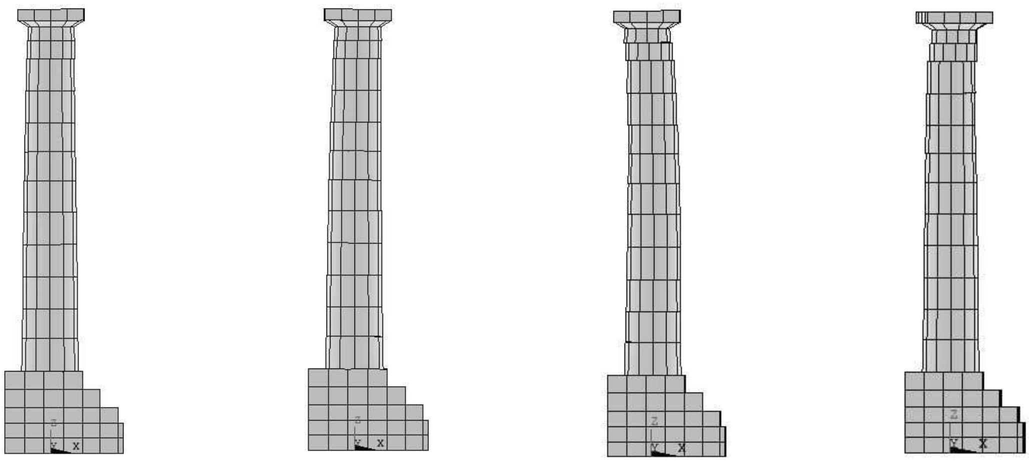
SEISMIC ANALYSIS OF THE MULTIDRUM COLUMN OF THE TEMPLE OF APOLLO

Maximum input PGA value

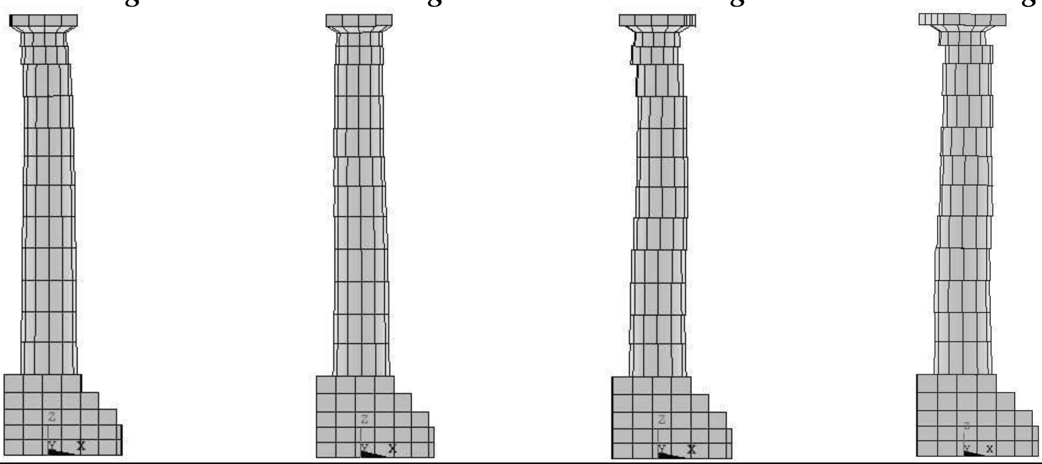
In order to examine the response of the restored multidrum column of Apollo Temple and to determine the maximum ground acceleration, which can sustain without collapse, we performed a specific parametric analysis with progressively increasing PGA values. We used four different seismic motions having different amplitudes and frequency content scaled from 0.4g to 1.0g (i.e. Aigio 1995, Erzincan 1992, Friuli 1976 and Kozani 1995).



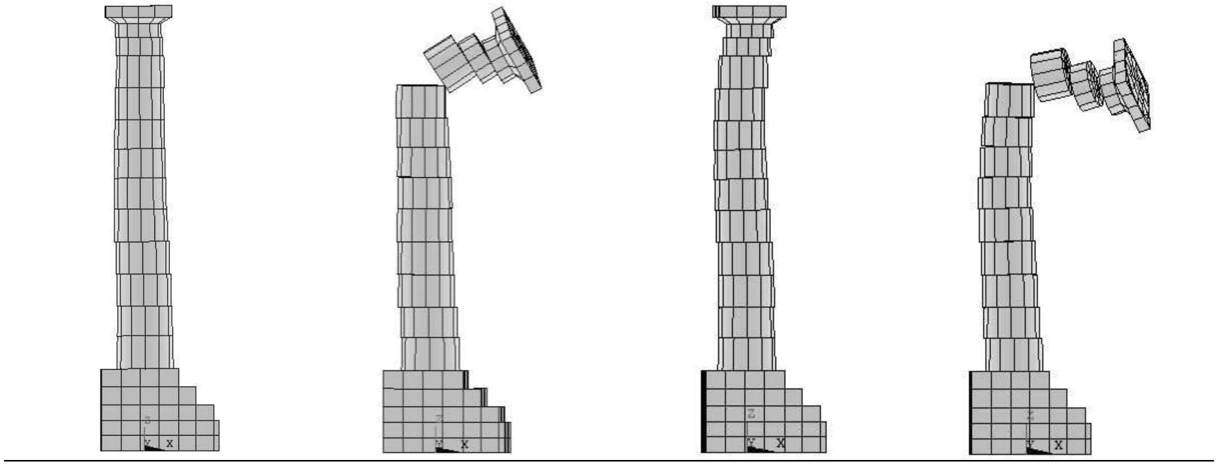
Aigio 0.5g ***Aigio 0.6g*** ***Aigio 0.7g*** ***Aigio 0.8g***



Kozani 0.5g ***Kozani 0.7g*** ***Kozani 0.9g*** ***Kozani 1g***



Friuli 0.5g ***Friuli 0.6g*** ***Friuli 0.8g*** ***Friuli 1g***



Erzincan 0.4g ***Erzincan 0.5g*** ***Erzincan 0.6g*** ***Erzincan 0.7g***

Figure 8: Response shapes of the multidrum column of the Temple of Apollo in Rhodes for the earthquakes of Aigio (1995), Erzincan (1992), Friuli (1976) and Kozani (1995) with PGA values scaled from 0.4g to 0.7g.

As it is observed in figure 8 the seismic response of the multidrum column of the Temple of Apollo is in general satisfactory. There are important relative displacements, but the column stands without collapsing, even for important PGA values. Only in the case of an earthquake like the Erzincan 1992 one, which is characterized of long period motions, the column is collapsing for PGA greater than 0.50g. It is important to notice that for input motion frequencies usually encountered for earthquakes in Greece, ancient multidrum columns can withstand large amplitude of PGA without collapse. However, a long period seismic excitation, such as the record of Erzincan 1992, may bring multidum columns to collapse even for relative small PGA values.

Modulus of elasticity and dynamic friction coefficient

In the previous studies, the columns are considered as being restored or reconstructed using the local limestone (E=1044MPa and v=0.25).

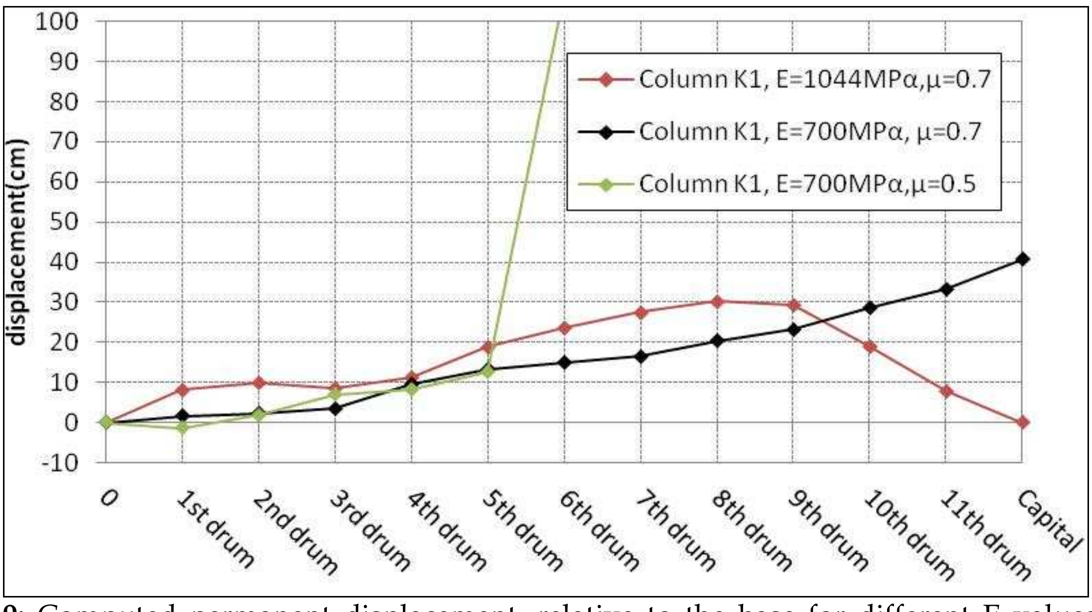
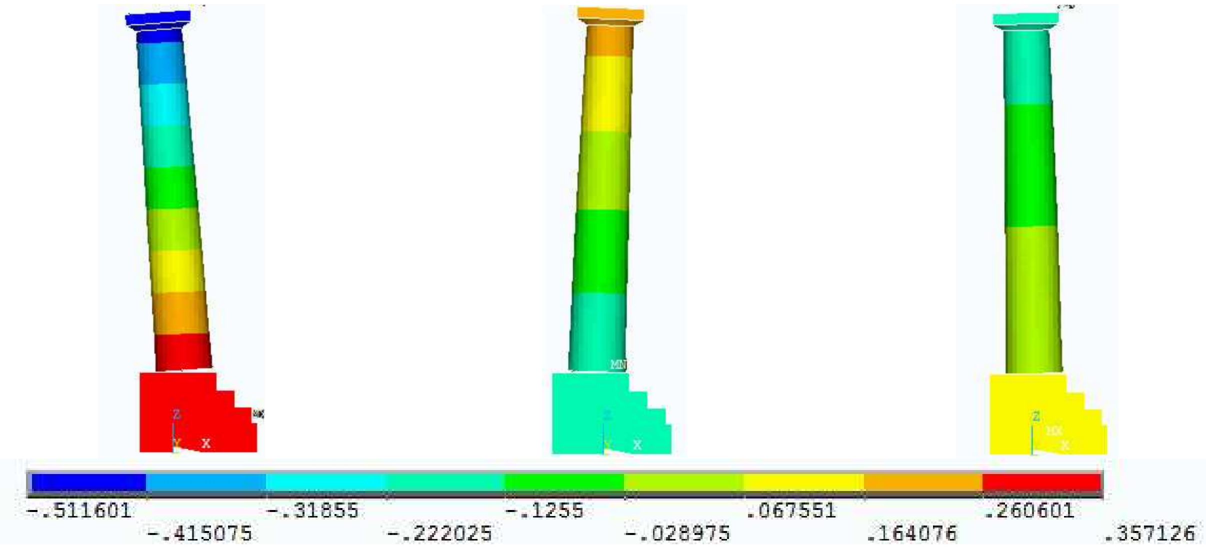


Figure 9: Computed permanent displacement, relative to the base for different E values. Input motion: Erzincan (1992) earthquake with PGA=0.6g, Multidrum column K1, Temple of Apollo.

In order to examine the effects of poor past restoration and the degradation of limestone properties with aging and unfavorable environmental condition, we examined the effect of reduced Young modules corresponding to different levels of deterioration of the local limestone used in the reconstruction, as well as reduction of the dynamic coefficient of friction at the contact surfaces.

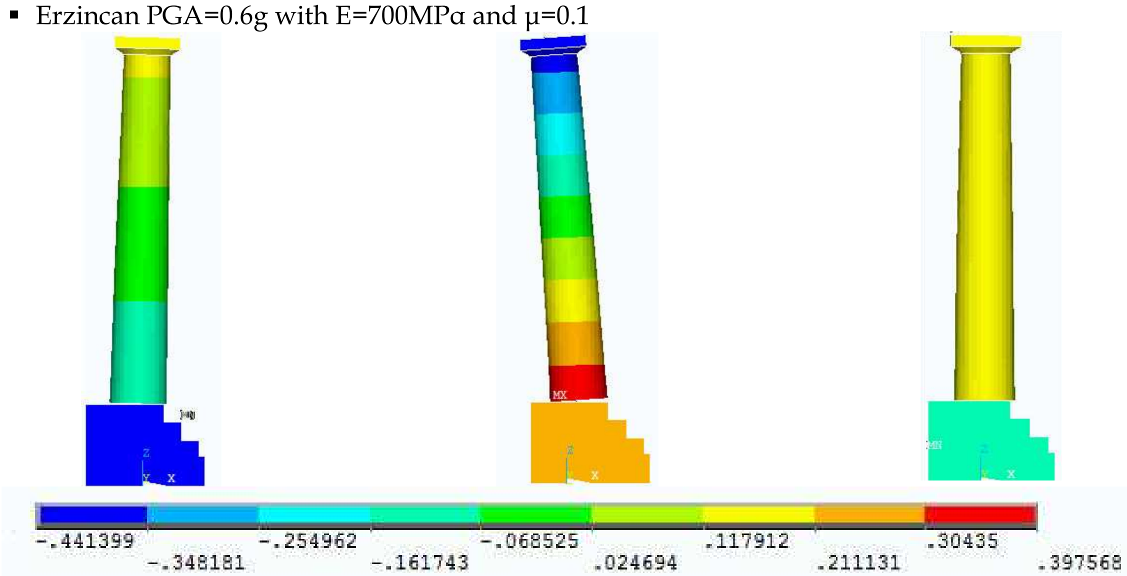
As the column becomes more flexible, with the reduction of Young modules values to E=700MPa, we observe larger in plane and out of plane displacements, the later being even three times larger. The same happens if we reduce the dynamic coefficient of friction from 0.7 to 0.5.

- Erzincan PGA=0.6g with E=700MPα and μ=0.5



t=4.2sec t=5.2sec t=7.7sec

- Erzincan PGA=0.6g with E=700MPα and μ=0.1



t=3.2sec t=4sec t=10sec

Figure 10: Typical seismic response images, at selected time windows, of the monolithic column of the Temple of Apollo in Rhodes. Earthquake: Erzincan (1992) with PGA=0.5g. Absolute displacements in m.

The monolithic column of the same geometry has the same response**.** Figure 10 presents the displacement patters of the Apollo column with E=700MPa and friction coefficients μ=0.5 and 0.1. For high values of the dynamic coefficient of friction (μ=0.5 and μ=0.7) the column response is mainly controlled by the rocking mode with no slide. On the contrary when the friction is reduced to a minimum value (μ=0.1), then the column response is basically controlled, as it is expected, by the sliding mode. Because of the large dimensions of the column we did not observed important twisting rotation.

CONCLUSIONS

The paper presents some characteristic results of the numerical study of two ancient Greek columns of two important temples in Rhodes. The finite element approach proved to be an efficient tool. However, due to the large sensitivity of the results to trivial changes of the parameters and the chaotic response of multidrum systems, special care must be taken in numerical analysis. The main conclusions are summarized as follow:

- During a strong earthquake, drums can slide differentially to each other and dissipate significant amount of energy through inelastic response. Moreover for higher values of coefficient of friction between drums, they may enter in rocking mode and twisting rotation with considerable out-of-plane displacements. Displacements and twisting rotation occur even for low PGA value ~~is low~~, especially at the capital.
- Normal and shearing stresses are not constant during the excitation; they are continuously altered and concentrations of shearing stresses at the interfaces are observed in particular moments when the drums are rocking.
- Multidrum columns may undergo several modes during the same excitation, thus no modes exist, with the classical meaning used in continuum mechanics, neither a fundamental period.
- The response of the monolithic column of the temple of Apollo (D/H=0.15) depends on the acceleration level and the dynamic coefficient of friction describing the contact shear strength between the interfaces. When the dynamic coefficient of friction is very low (<0.15), the column response is controlled, independently of the input acceleration, by the sliding mode. For high values of dynamic coefficient of friction, the response is controlled by the rocking mode.
- Generally the seismic response of the multidrum column of the temple of Apollo is satisfactory even for high acceleration input values. However it is observed that long period seismic excitation may increases considerably the vulnerability for these structures, compared to input motion with predominant high frequencies.
- The reduction of Young modules values and dynamic coefficient of friction leads to larger in plane and out of place displacement, and may produce the collapse of the multidrum column.

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