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NUMERICAL INVESTIGATION OF THE SEISMIC RESPONSE OF HEPHAESTUS TEMPLE IN ATHENS, GREECE

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Abstract. *In this paper, the seismic response of the Temple of Hephasteus in Athens, Greece is investigated numerically. The temple of Hephaestus was probably erected between 460 and 420 BC by a yet unknown architect on top of Agoraios Kolonos hill, which is delimiting the Ancient Agora of Athens to the west. It is one of the best preserved ancient temples, partly because it was transformed into a Christian church. The analyses were performed using the general purpose code 3DEC, which is based on the distinct element method, and can capture well the dynamics of multi-block systems, which respond to strong earthquakes with intense rocking and sliding of the individual blocks. The ground motions that were used as base excitations were selected to be compatible with the seismotectonic environment of the ancient center of Athens and within the range of the maximum expected earthquakes. In the numerical model, the full monument was implemented, but an investigation of the accuracy obtained with sub-models concerning small parts of the temple was also performed. The structural members were simulated quite accurately, but the columns and the walls were modeled intact, without the imperfections and the damage observed in the current state of the monument. However, the computer codes that were used were producing damage to the structure after each earthquake. In this way, it was possible to evaluate the effectiveness of the used software by comparing the predicted damage with the existing one.*

1 INTRODUCTION

1.1 Description of the structure

The Temple of Hephaestus, mostly known as Thision, dedicated to god Hephaestus, protector of blacksmiths and metallurgy, and to goddess Athena Ergane, is one of the most well preserved Doric peripteral temples [Figure 1]. Built between 460 and 420 BC by a yet unknown architect, to whom, however, are attributed other temples of similar structure in the Attica region, the temple is located on top of the Agoraios Kolonos hill, on the west side of the Athenian Agora in the historical center of Athens.

During the raid of the Heruli and later of the Goth the temple was left intact, and it was around 700 CE that the temple was converted to a Christian church, dedicated to Saint George. During that period, some alterations were conducted, including the shifting of the main entrance to the opisthodomos, the removing of the marble floor, the opening of two new entrances at the long side of the walls of the cella, and a cupola that was constructed over the cella. The last divine liturgy in the temple took place in 1833 during the celebrations for the arrival of Otto in Greece. After that, the temple was used as an archaeological museum, until 1930 when excavations were conducted in its interior by the American School for Classical Studies.

Figure 1. East view of Temple Hephaestus.

Figure 2 shows the temple in plan view. The structure, a peripteral temple of Doric order, consists of the Opisthodomos, the Cella, the Pronaos and the external colonnade. It is made of marble that was quarried at the Penteli Mountain from where the marble of the Parthenon also originates. The dimensions of the base are 31.80 m × 13.80 m. The Cella is 22.50 m long and 7.85 m wide. The external colonnade has six columns at the east and the west facades and thirteen columns at the north and the south facades. Each column consists of seven (7) drums of different height. The total height (drums and capital) of the columns is 5.70 m and the diameter at the base is 0.95 m.

Vertically, the temple can be divided in three parts (Figure 2): the crepidoma, the columns and the entablature. The crepidoma provides the surface on which the columns and the walls are placed and is comprised with several layers of squared stone blocks. The capital of the columns is made of a circular torus bulge, the echinus and a square slab called the abacus. The capitals support the entablature, which consists of two parts: the architraves (lowest part) and the frieze. The architraves consist of two beams at each span between adjacent columns.

The origin of the imperfections and damages observed in the current state of the monument differs. Some have been attributed to human intervention, such as the undercutting of the columns (Figure 3a) that took place for the placement of the sarcophagi in the peristyle [1, 2]. Others, such as the opening of the joints between the architrave beams at the corners of the temple (Figure 3b), are probably the result of several earthquake events that have hit Athens.

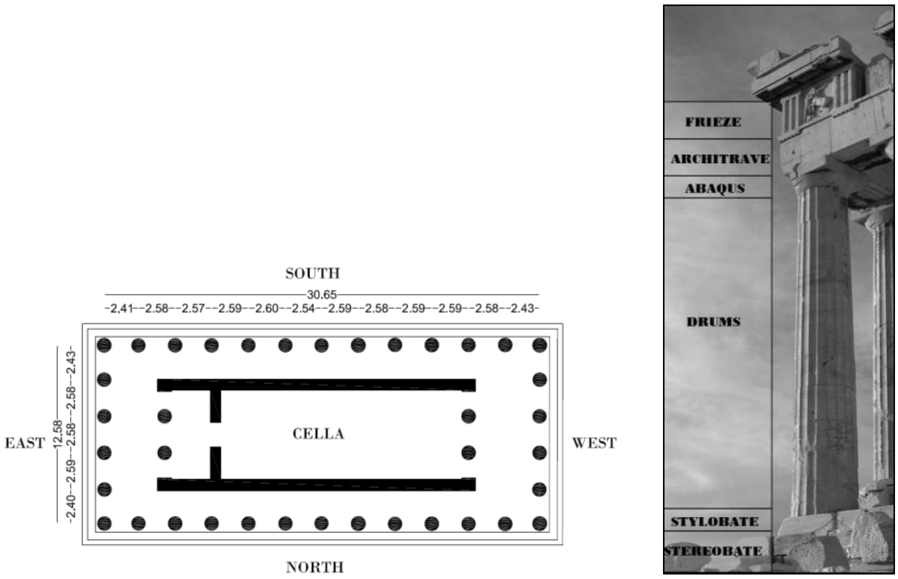


Figure 2. Plan view and elevation of Temple Hephaestus.

Figure 3. (a) Cutoffs of the lower drums of the columns at the north side of the temple; (b) opening of the joints of the architraves at the corners of the temple.

1.2 Numerical Simulation

Due to their spinal construction, the dynamic behaviour of ancient monuments is highly nonlinear and very sensitive to even trivial changes in the geometry or the base motion characteristics. During a seismic event, rocking and/or sliding of blocks (drums in case of columns), individually or in a group, can occur, leading to large displacements and rotations. For the numerical analyses presented in this paper, the code 3DEC by Itasca Consulting Group, Inc. [4] was employed, which is based on the discrete element method. The code was initially designed for the analysis of the behaviour of rock masses, which are modeled as assemblies of discrete rigid bodies and discontinuities are considered as boundary conditions. Large displacements and rotations and even complete detachment of the blocks is permitted, while the code automatically detects new contacts during the response. For rigid block problems, the code gives an accurate contact formulation, in which the interaction takes place at a number of contact points–. The contact between two blocks is represented by several sub-contacts where various types of contact are considered (apex to apex, apex to edge etc.) and interaction forces are applied. Each contact is assigned a contact area, which is used to calculate the local point stiffness, in terms of the user-defined normal and shear stiffness of the discontinuity surface. In addition a damping coefficient is introduced. The values of the joint stiffness used in the model were 5×10^9 Pa/m in the normal direction and 1×10^9 Pa/m in the tangential direction, based on values that were derived by comparing numerical results with corresponding experimental data obtained from shaking table tests performed at the Laboratory for Earthquake Engineering of the National Technical University of Athens [5-8].

In Figures 4 and 5, the numerical model of the temple of Hephaestus is shown. To simplify the simulation, without influencing the dynamic characteristics of the structure, the architectural details of the architraves and frieze, the flutes of the columns and the curvature of the stylobate were omitted. In addition all the drums of the external colonnade were considered with equal height. The cella was included in the model without taking into account any discontinuities. As in reality, it is connected to the exterior colonnade through beams located above the level of the entablature.

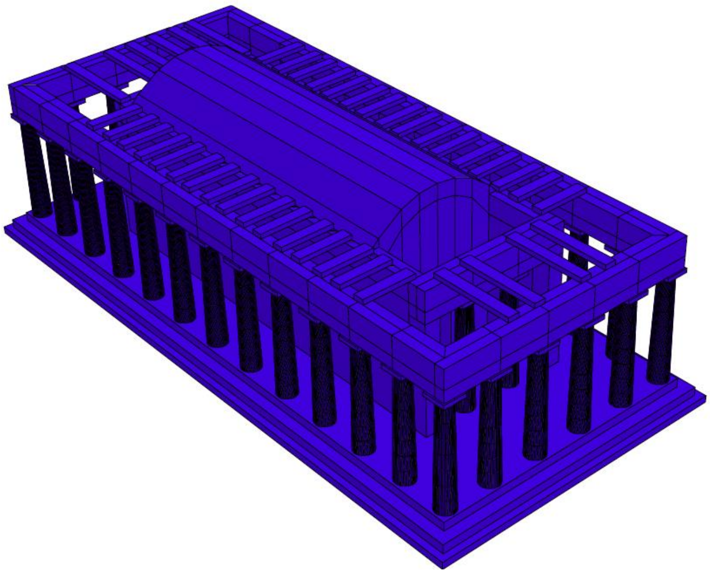


Figure 4. 3d view of the numerical model used in the analyses with 3DEC.

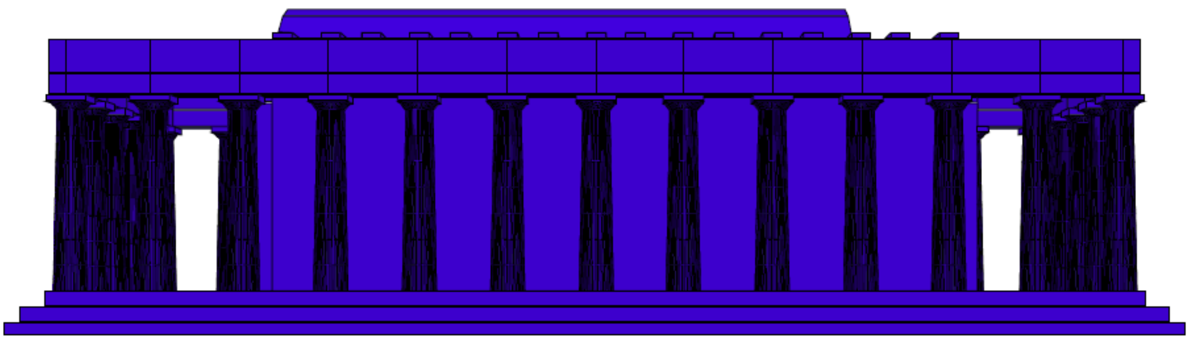


Figure 5. Side view of the numerical model used in the analyses with 3DEC.

2 SELECTION OF BASE MOTIONS

For the selection of the earthquake records to be used in the analyses, the records considered in [9], which are compatible with the seismotectonic environment and the ground profile of the historical center of Athens were selected. According to the results presented in [9], where back analyses on a free standing column of Thrasyllos, which is located nearby the Temple of Hephaestus, were performed, the maximum earthquake that could have happened in Athens during the last 2,300 years is unlikely it had peak ground velocity (*pgv*) larger than 35 cm/s and predominant period in the range 0.5–1.2 s which is consistent with the results of seismotectonic analyses. Within this range of the maximum expected earthquakes, the model was subjected to the ground motion of four earthquakes amplified accordingly [9]. The main parameters of the seismic input motions are shown in Table 1. Both horizontal components and the vertical one of the considered records were applied simultaneously as the base motion to the numerical model.

Earthquake record	Magnitude M_w	Fault dist. [km]	Amplification factor	Long		Trans	
				pga (m/s^2)	*pgv* (m/s)	*pga* (m/s^2)	*pgv* (m/s)
Syntagma-B (1999)	5.97	10	3.5	1.07	10	0.84	11
Assisi-Stallone (1997)	6.04	14	2.0	1.84	10	1.64	8
Cascia (1979)	5.89	1	2.5	1.42	8	1.99	11
Kozani (1995)	6.61	14	2.5	2.13	9	1.38	7

Table 1: Earthquake records considered in the numerical analyses.

3 RESULTS

Indicative results are presented in Figure 6 which shows the time-histories of the displacements at the capital of three columns (the two corner column and one middle column) located at the north façade. With the exception of the response for the Assisi-Stallone earthquake, the three columns exhibited somehow different displacements and rotations despite the symmetry in the external collonade itself. It is noted, though, that there is a small asymmetry in the connections of the collonade to the cella. The maximum displacement of the capital was observed during the Syntagma-B excitation (amplified 3.5 times) and had a value of 8 cm. The maximum permanent dislocation at the capital was 2.4 cm, whilst, for all excitations, larger values were observed at the middle drums of the columns, a fact that conforms with the current state of the temple (see Figure 7).

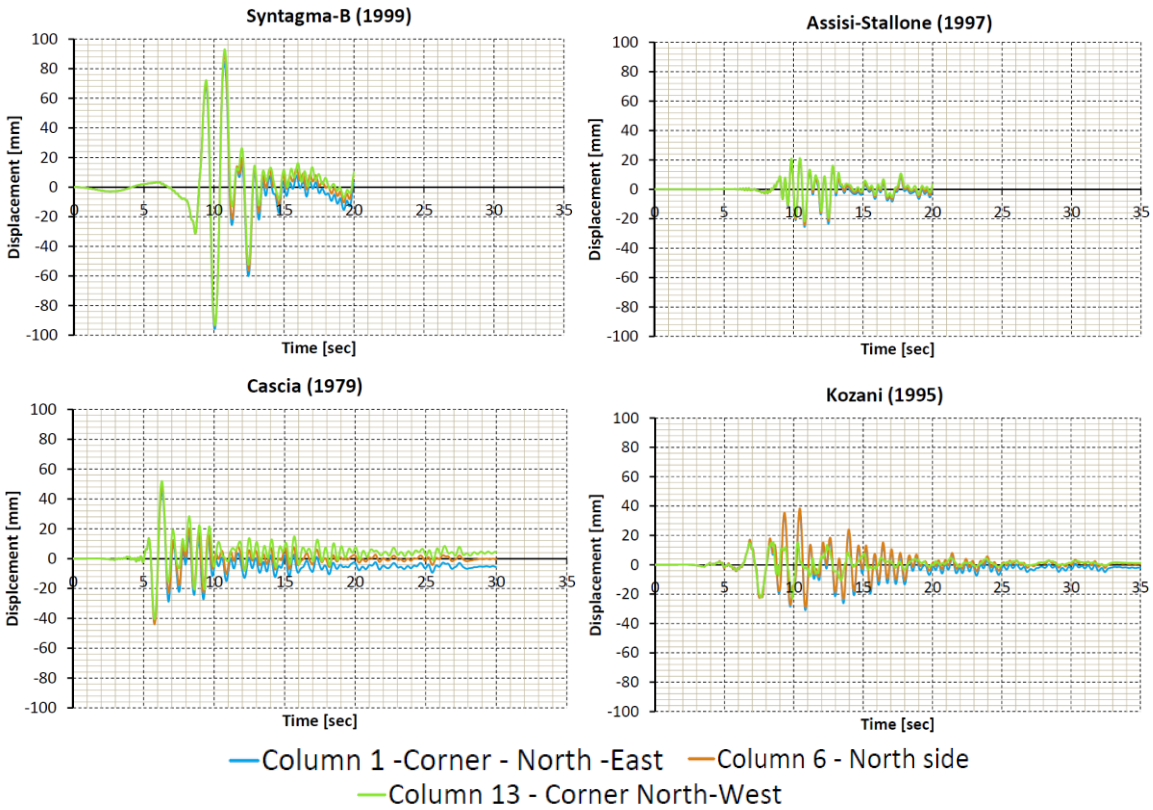


Figure 6. Capital displacements of three columns (the two corner column and one middle column), located at the north façade.

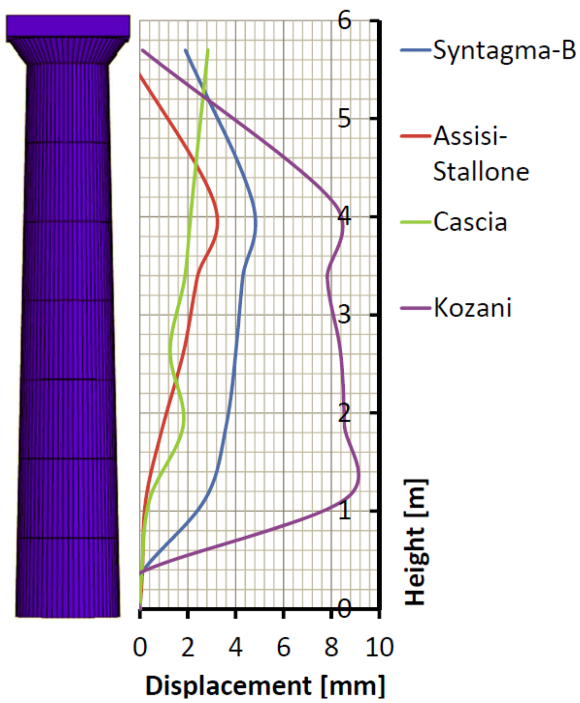
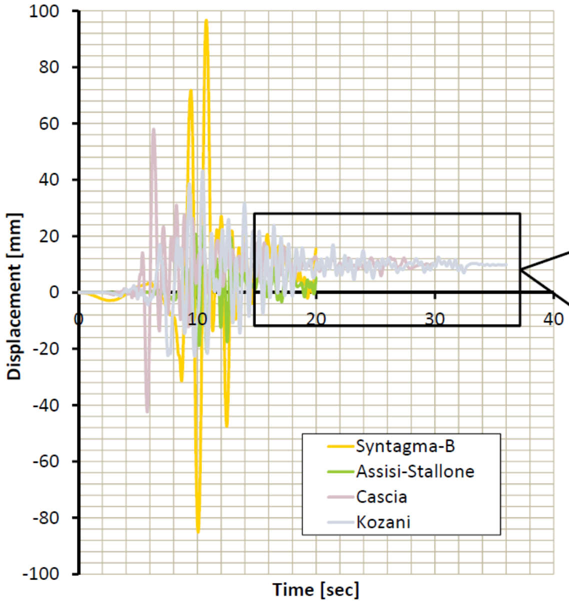


Figure 7. Residual displacements along the height of the corner column.

Figure 8 shows the time-history of the displacement of the outer architrave at the corner of the temple. It can be seen that, for all excitations, significant permanent displacement is evident, which led to the opening of the joint between the architrave beams. It should be noted that experiments performed in a 1:3 scale model of three columns with architraves [8] indicated that existing dislocations from previous earthquakes may enlarge the displacements during future seismic events compared to the intact structure.



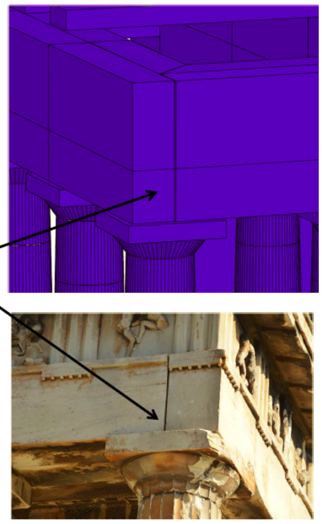


Figure 8. Time-history of the displacement of the outer architrave at the corner of the temple.

4 SUB-MODELS

4.1 Numerical Model

The dynamic analysis of the complete structure of a monument is difficult and very time-consuming, which leads to the necessity to create sub-assemblies in order to make their study more efficient without compromising with the accuracy of the results. In order to check whether such an approach is acceptable, a sub-assembly of the corner of the temple was created and compared to the full model presented above. In the sub-model, four columns of the long side and two columns of the short side were considered, keeping the same ratio of the number of columns on these sides as in the actual structure (13:6).

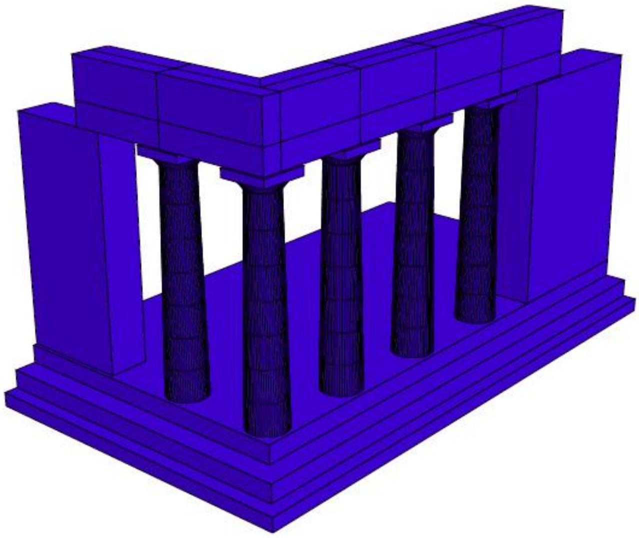


Figure 9. 3d view of the sub-model considered.

4.2 Results

In Figure 10, the residual displacements along the height of the corner column obtained from the complete model and the sub-model are depicted. In the case of the Assisi-Stallone and the Cascia excitations, the results are similar, but in the case of the Syntagma-B and the Kozani earthquakes, larger displacements occurred full model and the form of the dislocations of the drums along the height of the column was different. Evidently, further investigation is needed regarding this important issue.

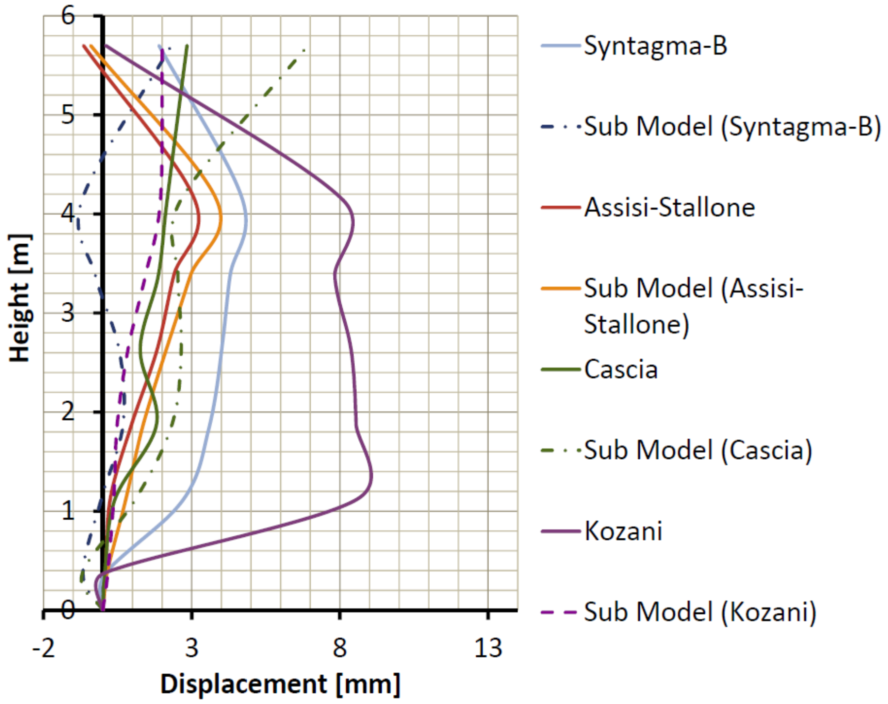


Figure 10. Comparison of the residual displacements along the height of the corner column

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