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SEISMIC BEHAVIOUR OF THE WALLS OF THE PARTHENON A NUMERICAL STUDY

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Abstract: *A numerical study of the behaviour of the walls of the Cella of Parthenon subjected to seismic loading is presented. Commonly used numerical codes for masonry structures based on continuum mechanics are unable to handle the behaviour of discontinuous walls of ancient monuments, in the same way as continuum models cannot capture the behaviour of drum-columns. In this analysis, the discrete element method was used, which has been proven, in previous research, capable to accurately predict the response of discontinuous structural systems. The marble structural stones of the walls were modeled as rigid blocks with frictional joints between them. Two types of models were used in the analyses: (i) a sub-assembly consisting of only a section of the wall of limited length, either as it is in-situ (partially collapsed) or with its full height (restored) and (ii) considering the whole structure partially restored. In one of the models of type (i), the existing damage of the stones was also implemented. Analyses were performed with and without considering the metallic elements (clamps and dowels) that connect adjacent stones. The numerical models represented in detail the actual construction of the monument. The assemblies considered were subjected to all three components of four seismic events recorded in Greece. Time domain analyses were performed in 3D, considering the non-linear behaviour at the joints. The general response profile was examined, as manifested by rocking and sliding of individual stones or groups of stones. The effect of several parameters was investigated including: the coefficient of friction at the joints, the imperfections of the blocks, the existence or not of connectors between adjacent blocks and the seismic motion characteristics. The results of the sub-assembly models and the full-structure model were compared in order to estimate the accuracy of the sub-structuring technique. The effect of the restoration of the wall to its original height was also examined. Conclusions were drawn based on the maximum displacements induced to the structure during the ground excitation and the residual deformation at the end of the seismic motion.*

1 INTRODUCTION

The restoration of classical monuments is a complicated and difficult task, first because any intervention should take under consideration the historical, aesthetical and archaeological values of the structure, and second because the structural analysis is quite complicated due to the spinal construction of classical monuments, which are comprised of massive, carefully fitted stone blocks without the use of mortar. Under static loading, the resulting stresses usually do not exceed 15% of the material's strength, owing to their large member sections. This percentage is further decreased in monuments of ruinous nature and thus, failure parameters and criteria should be based on member displacements rather than material failure.

During strong seismic events, the response is dominated by the rocking and the sliding of the structural elements. This behaviour, which is highly non-linear and complicated, is practically impossible to be treated in an analytical manner and can only be handled numerically. So far, a number of numerical studies [1-7] or experimental investigations [8-10] on drum-columns, either free-standing or connected with architraves, have been presented. Comparison of numerical results with shake table experimental data on drum-column marble models [2, 6] showed that the distinct element method and especially the code 3DEC of Itasca Consulting Group, Inc [11] can predict reasonably well the response of such structures, despite the sensitivity of the behaviour to even trivial changes of the parameters.

The earthquake response of walls of classical monuments is different than the response of multi-drum columns, because the structural blocks are interlocked from the way that the masonry is constructed and, usually, they are connected with metallic elements. The dynamic response of columns is prevailed by rocking while in walls, the response is governed mainly by sliding and less by rocking, which can only occur in the out-of-plane direction. However, since the discrete element method can consider both sliding and rocking, it can be applied for the assessment of the earthquake response of stone masonry.

In this paper, an investigation of the seismic behaviour of the walls of the Cella of the Parthenon on the Acropolis of Athens, Greece is presented. Four ground motions, recorded during recent earthquakes in Greece, were used as base excitations. Two series of analyses were performed: (i) using sub-assembly models consisting of only a section of the wall of length equal to 4.88 m at its base (four stones), either as it is in-situ (partially collapsed) or restored to its full height and (ii) considering the whole structure, partially restored compared to its present condition. In both cases, analyses were performed with and without considering the connections between the stones. In case (i), the major structural imperfections due to damage were also considered in some runs.

2 DISCRETE ELEMENT MODELING OF STONE MASONRY

During the seismic response of discontinuous block assemblages, the deformation and failure is dominated by the movement between individual blocks. Resultantly, continuum models, based primarily on the finite element method, may not be appropriate numerical tools for identifying key features of the response or efficiently handling significant sliding along joints. Instead, discontinuous modelling via the discrete element method tends to function better in that role.

In this paper, the code 3DEC [11] that is based on the discrete element method was used in the analyses. In the distinct (or discrete) element method (Cundall [12]), the system is represented as an assembly of discrete blocks. Joints are viewed as interfaces between distinct bodies, allowed to undergo unlimited translation and rotation including complete detachment from adjacent blocks. New contacts are automatically recognized as the calculation progresses. At each contact surface, relationships are established that associate the normal and the shear forces to displacements. The method is usually applied to systems in which the behaviour is dominated by discontinuities and the material elastic properties may be ignored. It is possible, however, to consider deformable blocks, which are further discretised in finite elements.

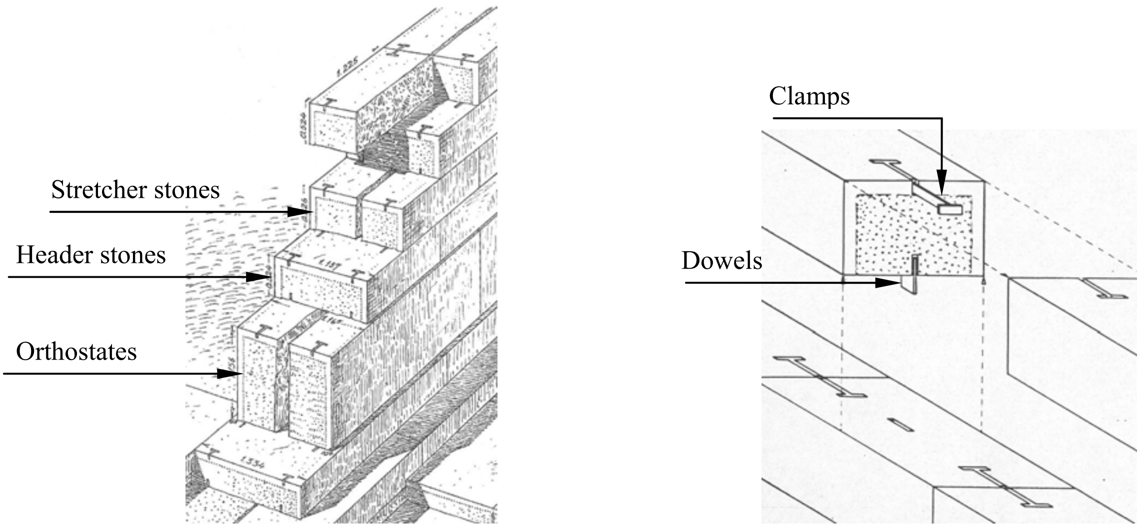
The dynamic response is calculated using a time-stepping algorithm. The time-step should be sufficiently small, so that disturbances cannot propagate between adjacent discrete elements during a single step. The required time-step is defined by the mass of the blocks and the stiffness and damping at the contacts. The solution scheme is identical to that used by the explicit finite difference method for continuum analysis.

3 DESCRIPTION OF THE MONUMENT

The walls of the Cella of the Parthenon are comprised of the row of the orthostates, situated at the base (in effect a row of stretcher stones of 1.16 m in height), followed by 17 alternating rows of header and stretcher stones (Figure 1a). The width of the header stones is 1.14 m, equal to the width of the wall, and that of the stretcher stones 0.55 m, which, consequentially, leaves a horizontal transverse gap of 4.0 cm width between the stretcher stones of the same row. The orthostate stones have also a width of 0.55 m and protrude outwards by 7 mm. All stones are approximately 1.22 m in length. Both header and stretcher stones are 0.52 m in height, resulting to a total height of the wall, in its original state, just over 10 m without including the architraves, i.e. the upper row of larger size stones.

Due to the absence of mortar, iron elements were initially used to connect structural members. Two types of connections were applied (Figure 1b): tensile clamps, placed at the top of each stone across vertical joints, and shear dowels, located at the base of each stone.

Today, only the W wall is in good condition, while the N, E and S walls are partially collapsed. Also, only small portions of the inner wall, at the places where it was connected to the N and S walls, are still standing. Most of the damage was caused during a large explosion that occurred in the interior of the monument in 1687. The inner side is heavily damaged and most stones suffer from cut-offs and wedge shaped notches, while many have been lost altogether. The detrimental effect of cut-offs to the stability of classical monuments has been previously investigated [3, 5]. However, the properties of the material, for instance its high compressive strength and modulus of elasticity, remain largely unaffected.



(a) (b)

Figure 1: (a) Cross-section of the Parthenon walls (reproduced from [13]); (b) Layout of the connecting elements (reproduced from [14]).

4 NUMERICAL MODELS

4.1 General assumptions

Two series of analyses were performed: in the first series, the model was based on a sub-assembly section of the wall with length at its base corresponding to four stones; in the second series, the whole structure, partially restored, was modelled. In both cases, analyses with and without considering the connecting elements between the stones were performed.

In all models, each stone was represented by a convex rigid block. For masonry structures composed of stones of hard material, as marble, the deformation of the system occurs mainly at the joints. Thus, it is reasonable to consider rigid blocks instead of deformable ones in order to reduce the run-times.

A Mohr–Coulomb constitutive model was adopted for the mechanical behaviour of the joints. No tensile strength was considered in the normal direction, in which the joint behaviour was governed by the normal stiffness coefficient that related the contact stress with the normal contact displacement. In the shear direction, an elasto-plastic stress-displacement law was assumed: the elastic range was characterized by the shear stiffness, while the shear strength was governed by the Coulomb friction coefficient with no cohesive strength component. For the normal and the shear stiffness, typical values for marble [2, 6] were used, while three values of friction coefficient were considered: μ=0.75, 1.0 and 1.15. The joint properties used in the analyses are listed in Table 1.

The clamps and dowels were considered as elasto-plastic elements with the properties shown in Table 2. These values were derived from the dimensions of the cross section of the connecting elements and the elastic properties of the material. In the prototype structure, the clamps and dowels were made of iron. However, for the part that will be restored, titanium connecting elements will be used. For this reason, the elastic properties of titanium were used in Table 2.

No damping was considered during the first 20 sec of the response, which cover the duration of the strong ground motion for all records, as proposed by Papantonopoulos et al [2]. However, mass proportional damping with a value of 20% of critical at 0.3 Hz was applied to the remainder of the response, in order to attenuate faster the motion of the structure after the earthquake and, thus, facilitate the determination of the residual displacements.

Parameter	Value
Normal stiffness (compressive)	1×10^6 KPa/m
Normal stiffness (tensile)	0
Shear stiffness (elastic branch)	1×10^6 KPa/m
Friction coefficient	0.75, 1.00, 1.15
Cohesion	0

Table 1: Mechanical properties of the joints.

Parameter	Clamps	Dowels
Axial stiffness	7×10^6 KN/m	-
Axial yield force	50 KN	-
Ultimate axial strain	20%	-
Shear stiffness	2.87×10^6 KN/m	1.3×10^6 KN/m
Shear yield force	25 KN	15 KN

Table 2: Properties of the connecting elements.

4.2 Sub-assembly models of a section of the N wall

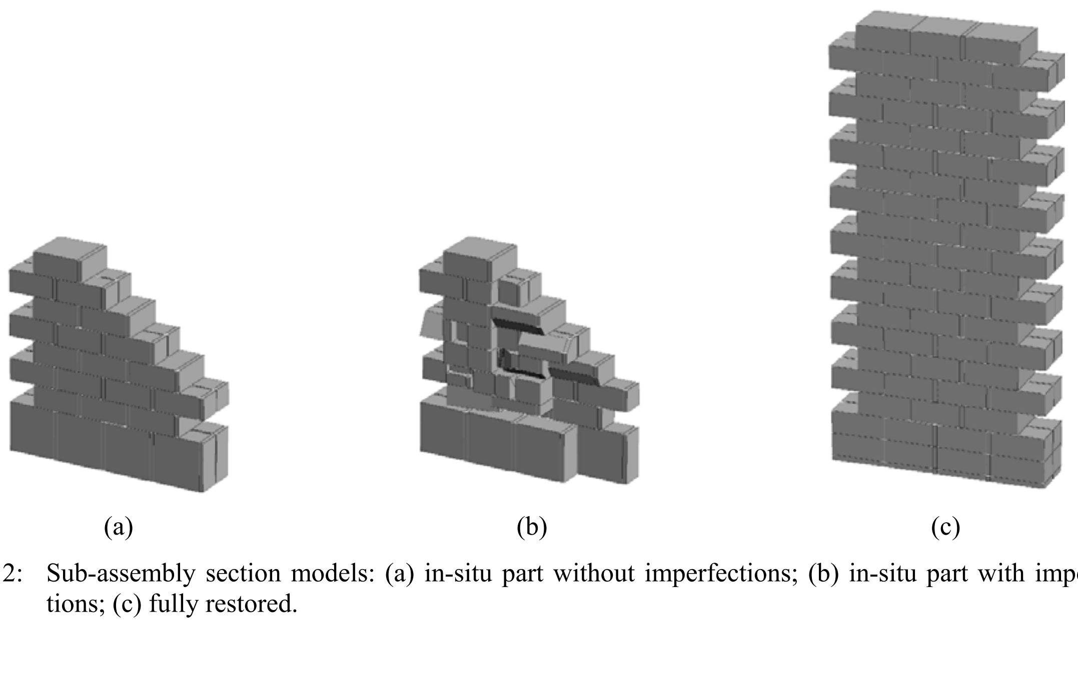
Three different geometrical models were considered for a sub-assembly section of the N wall, namely: (a) the in-situ, partially collapsed portion of the easternmost surviving part of the N wall with stones without imperfections, as in their initial, intact state (Figure 2a); (b) the same in-situ part, but taking into account all major structural imperfections due to the existing damage (Figure 2b); and (c) the same part of the wall fully restored to its original height, without imperfections (Figure 2c).

The height of the in-situ segment was 4.80 m, its width 1.14 m and its length 4.88 m at the base. For the model with imperfections, cut-offs were considered on selected stones, simulating the existing damage. The fully restored wall segment had a height of 10.0 m, width of 1.14 m and the same length with the in-situ model, equal to 4.88 m.

For the sub-structure models, the connections between the blocks, when considered, were applied using a simplified assumption: since the connecting elements are evenly distributed, their influence was considered by modifying the joint properties instead of accurately modelling each one of them. Thus, in order to count for the longitudinal strength of the clamps, normal tensile strength was added to the vertical joints, equal to the total tensile strength of the clamps connected to each joint. The shear strength of the dowels and the clamps was considered by adding cohesion to the joints, equal to the total shear strength of the corresponding elements divided by the area of the contact surface. The accuracy of this simplified approach was verified, for selected cases, through a comparison with the results of the corresponding model with the actual connecting elements. Such comparisons showed that the maximum displacements during the strong ground motion were almost identical and that the residual deformations were similar.

4.3 Full model of the partially restored structure

The model of the full structure (Figure 3) was based on a restoration scenario, according to which the monument is partially restored. In this model, all the geometrical details of the prototype and an exact representation of the connecting elements were implemented. All the stones were assumed intact, without damage. The parts of this model that are marked with the boxes A and C in Figure 3 can be assumed representative of the sub-assembly models (a) and (c) of Figure 2, respectively; thus, comparison of the results is possible.



(a) (b) (c)

Figure 2: Sub-assembly section models: (a) in-situ part without imperfections; (b) in-situ part with imperfections; (c) fully restored.

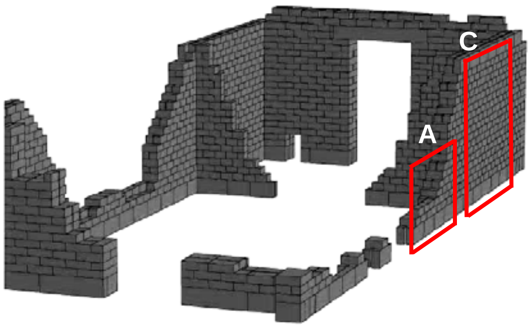


Figure 3: Full model of the partially restored structure. The boxes A and C correspond to the sub-assembly section models (a) and (c) of Figure 2, respectively.

5 SEISMIC INPUT

All the analyses were performed in 3-D, applying all three components of each seismic motion at the base of the models. Four records of recent strong earthquakes in Greece were used (Figure 4 and Table 3):

- The Kalamata, 1986 (Ms=6.2) accelerogram that was recorded on stiff soil at a distance of about 9 km from the epicentre. The record samples the near-field strong motion characteristics that caused considerable damage to the buildings of the city of Kalamata. The duration of the strong motion is about 6 sec.

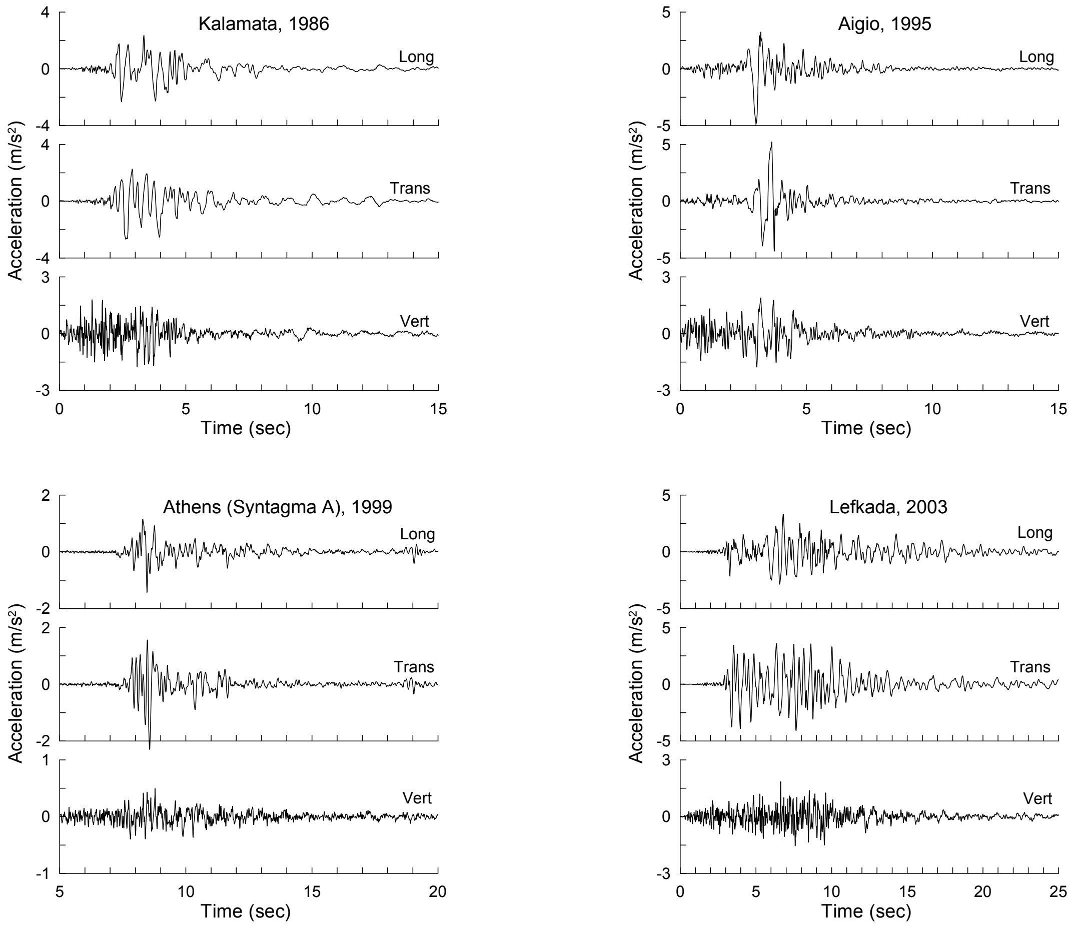


Figure 4: Earthquake records considered in the analyses.

	Longitudinal direction		Transverse direction	
Earthquake	PGA (g)	PGV (m/sec)	PGA (g)	PGV (m/sec)
Kalamata, 1986	0.24	0.32	0.27	0.24
Aigio, 1995	0.49	0.44	0.53	0.46
Athens, 1999	0.15	0.13	0.23	0.14
Lefkada, 2003	0.34	0.30	0.42	0.31

Table 3: Peak ground accelerations and velocities of the two horizontal components of the earthquake records considered in the analyses.

- The Aigio, 1995 (Ms=6.2) accelerogram that was recorded 18 km away from the epicentre. The record was obtained at the basement of a two-storey building on rather soft soil and it is dominated by a 0.5 sec period pulse of approximately 0.53 g amplitude in the main horizontal direction.
- The Athens, 1999 earthquake (Ms=5.9), that was recorded at the Metro station at Syntagma, on firm soil (schist) at a depth of approximately 7.0 m below the ground surface. The site was about 20 km away from the epicentre and located close to the Parthenon, in a distance of less than 1 km.
- The Lefkada, 2003 (Ms=5.8) accelerogram that was recorded near the causative fault on rather soft soil. The record was influenced by near-field effects of backward directivity, showing a long duration of about 10 sec.

In all the analyses, the stronger horizontal component of each earthquake was applied to the normal direction of the long walls (N-S direction).

The results obtained using the Athens record showed significantly smaller deformations compared to the other earthquakes. For this reason, they are not presented in the following. It should be noted that such small deformations were expected for this record, because the displacements that occurred at the monument, during the actual seismic event, were indeed small.

6 PRESENTATION OF THE RESULTS

6.1 In-plane vs out-of-plane response

Figures 5 and 6 show a comparison between the in-plane and the out-of-plane maximum (during the ground shaking) and residual displacements along the height of the wall, respectively. These results correspond to position C and were obtained using the full-structure model of Figure 3 for the Lefkada record, normalized to pga=0.20g. It can be observed that the residual displacements are similar in both directions, but the maximum displacements are significantly larger in the out-of-plane direction. For this reason, only results in the out-of-plane direction are presented in the following.

6.2 Effect of friction coefficient

Previous experimental investigation on shear cyclic tests of marble joints [15] showed that there is a dependence of the friction coefficient on the vertical load and on the velocity of application of the shear displacement. These experiments were performed using specimens made of Dionysos marble, the same material of which the Parthenon is constructed. The values obtained for the residual friction coefficient were varying from 0.7 to 1.2, approximately, showing the uncertainty that exists concerning the appropriate value that should be used in the analysis. For this reason, a parametric investigation was performed for three values of the friction coefficient, namely: μ=0.75, 1.00 and 1.15.

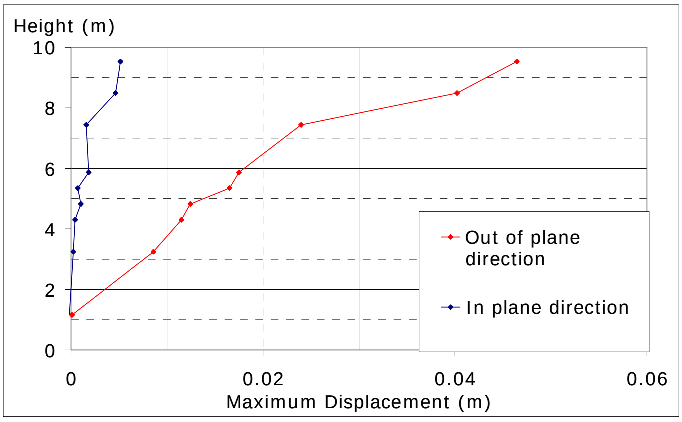


Figure 5: Maximum displacements along the height of the full-structure model at position C (Lefkada earthquake normalized to pga=0.20g).

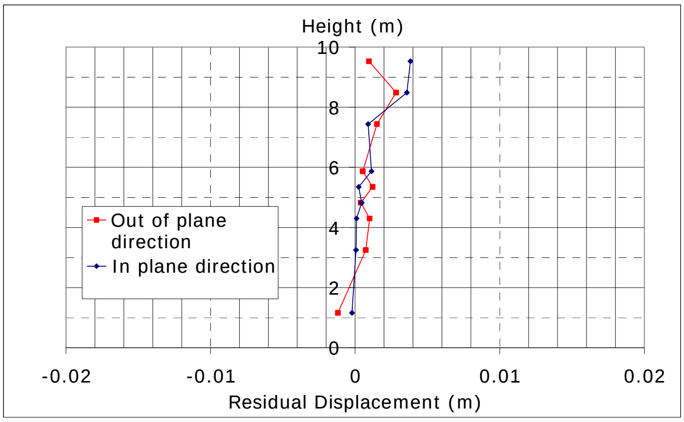


Figure 6: Residual displacements along the height at position C of the full-structure model (Lefkada earthquake normalized to pga=0.20g).

In Figures 7 and 8, the maximum displacements and the residual deformation, respectively, in the out-of-plane direction along the height of the wall of the sub-assembly models of Figure 2, without connections, are ploted. The displacements shown are relative to the base, thus any base dislocation has been subtracted. Concerning the maximum displacements during the ground shaking, it seems that, practically, friction does not influence the response. For the permanent displacements, the effect of friction is not monotonic and changes with the earthquake characteristics: for the Kalamata earthquake, an increase in the friction coefficient generally decreases the residual displacement at the top of the structure but it increases the deformation at lower positions while for the Lefkada earthquake the opposite behaviour is observed.

Similar results were obtained for the full-structure model of Figure 3. The top maximum and the residual displacements in this case are given in Tables 4 and 5, respectively.

It should be noted that, according to the results presented in [15], the value of μ=0.75 is approximately the average residual friction for a wide range of expected velocities. Also, comparison of numerical results with experimental data for the seismic response of marble multi-drum model columns, presented in [2] and [6], showed that good agreement could be obtained if a friction coefficient around 0.75 was considered. Based on these observations and the relatively small dependence of the response on the friction coefficient, results for only μ=0.75 are presented in the following.

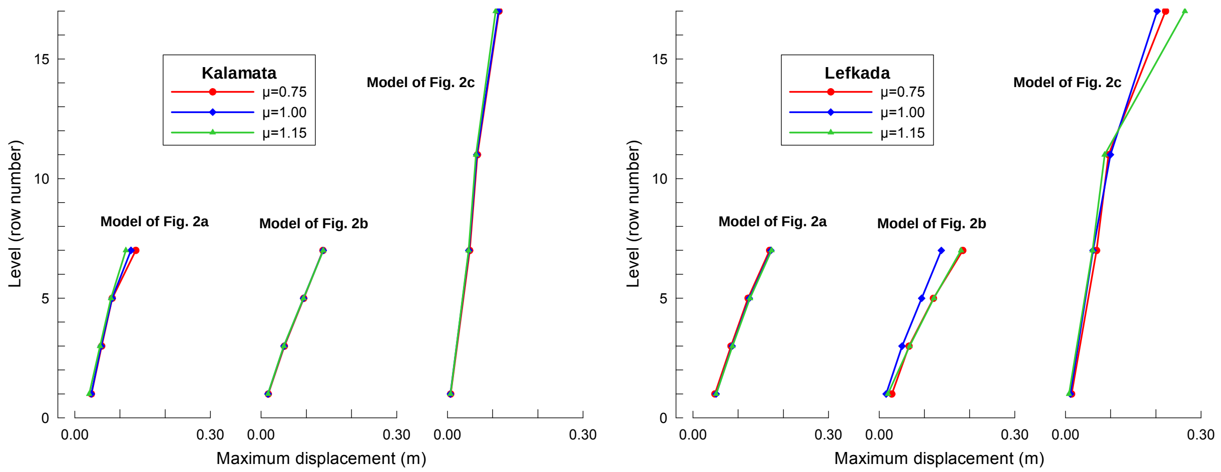


Figure 7: Effect of friction coefficient to the maximum displacements in the out-of-plane direction.

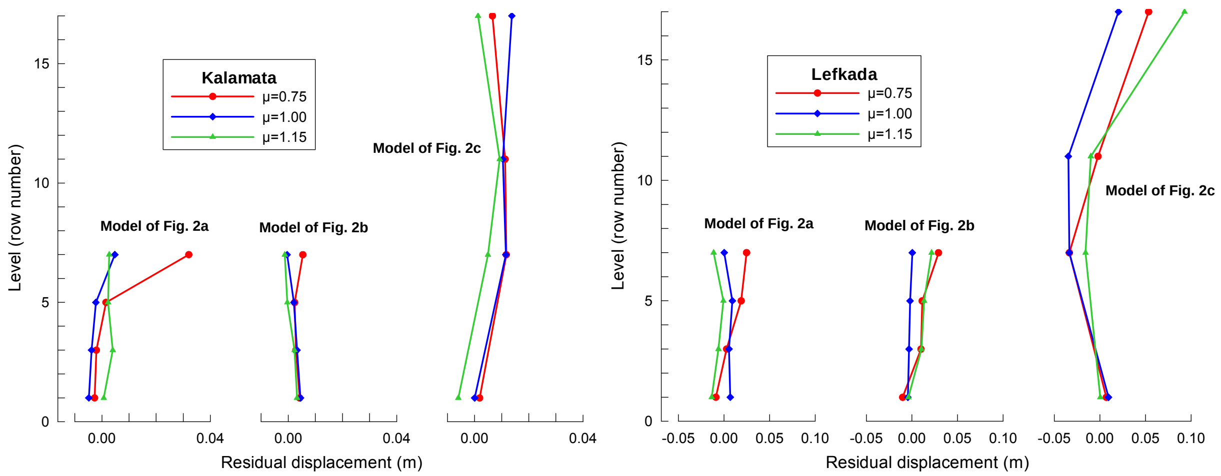


Figure 8: Effect of friction coefficient to the residual deformation in the out-of-plane direction.

	Position A		Position C	
Earthquake	μ=0.75	μ=1.00	μ=0.75	μ=1.00
Kalamata	0.026	0.028	0.095	0.102
Aigio	0.056	0.057	0.092	0.092
Lefkada	0.076	0.062	0.116	0.125

Table 4: Top maximum displacements (m) in the out-of-plane direction at positions A and C of the full-structure model (Figure 3).

	Position A		Position C	
Earthquake	μ=0.75	μ=1.00	μ=0.75	μ=1.00
Kalamata	0.007	0.008	0.014	0.013
Aigio	0.013	0.018	0.068	0.043
Lefkada	0.028	0.024	0.050	0.062

Table 5: Top residual displacements (m) in the out-of-plane direction at positions A and C of the full-structure model (Figure 3).

6.3 Comparison of the sub-assembly models with the full-structure model

The results obtained with the simplified sub-assembly models of Figure 2 were compared to the corresponding results for positions A and C (Figure 3) of the full-structure model. The simplified model gave, in all cases, larger maximum top displacements. This was expected, since the section of the wall considered in the sub-assembly models behaves as a free-standing cantilever, being, thus, more flexible than the corresponding part of the whole structure, where the contribution of the transverse walls increases the stiffness and rather prevents rocking.

In Figure 9, the time-history of the top displacement of model (c) of Figure 2 and the corresponding one at position C of the model of Figure 3 are presented for the Lefkada earthquake. The long-period vibrations of the simplified model, which are evident after the strong part of the ground shaking, imply that the motion is governed by rocking. In the contrary, the response of the full-structure model shows high frequency characteristics; in this case, sliding seems to be the prevailing deformation mode.

For the sub-assembly model, the predominant role of rocking was also verified from the fact that the out-of-plane displacements of the stones were increasing monotonically with the height and the maximum displacements occurred simultaneously for all blocks. In the contrary, the residual displacements, which are caused mainly by the sliding of the stones, did not show a monotonic pattern with height and displacements of opposite signs were recorded.

It should be noted that, in most cases, the residual displacements of the full-structure model were larger than the corresponding ones of the simplified sub-assembly models. This is in accordance with the above drawn conclusion that the full-structure model responds more in sliding and less in rocking.

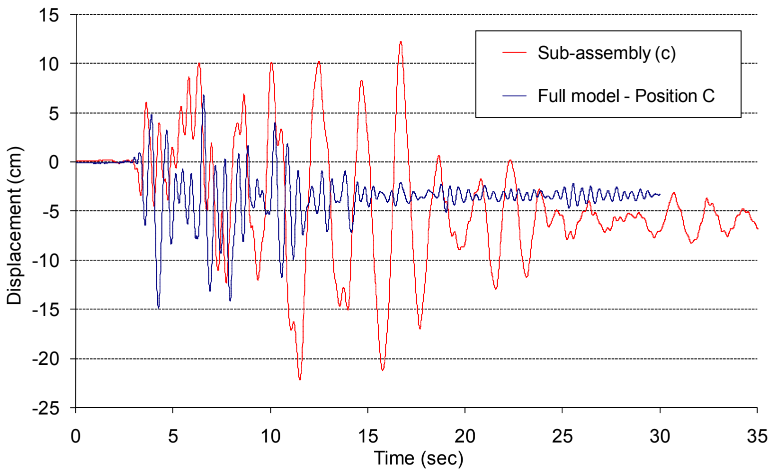


Figure 9: Time history of the top displacement in the out-of-plane direction of model (c) of Figure 2 and at position C of the full-structure model (Figure 3) for the Lefkada earthquake.

6.4 Effect of connections

Tables 6 and 7 summarize the results of the full-structure model with and without connections. It is interesting to note that, in many cases, the maximum top displacement in the out-of-plane direction was larger if the blocks were connected with clamps and dowels than if not. This should be attributed to the fact that connections force the walls to respond more in rocking and less in sliding, increasing thus the displacements. The rocking that occurs at position C when the blocks are connected is evident in Figure 10 from the large vibrations that are observed after the end of the strong ground shaking. This phenomenon was pronounced more at the full-height part of the wall (position C) and less at parts of small height (e.g. position A).

	Position A		Position C	
Earthquake	With connections	Without connections	With connections	Without connections
Kalamata	0.040	0.026	0.064	0.095
Aigio	0.052	0.056	0.151	0.092
Lefkada	0.063	0.076	0.149	0.116

Table 6: Top maximum displacements (m) in the out-of-plane direction at positions A and C of the full-structure model (Figure 3).

	Position A		Position C	
Earthquake	With connections	Without connections	With connections	Without connections
Kalamata	0.008	0.007	0.006	0.014
Aigio	0.005	0.013	0.025	0.068
Lefkada	0.011	0.028	0.033	0.050

Table 7: Top residual displacements (m) in the out-of-plane direction at positions A and C of the full-structure model (Figure 3).

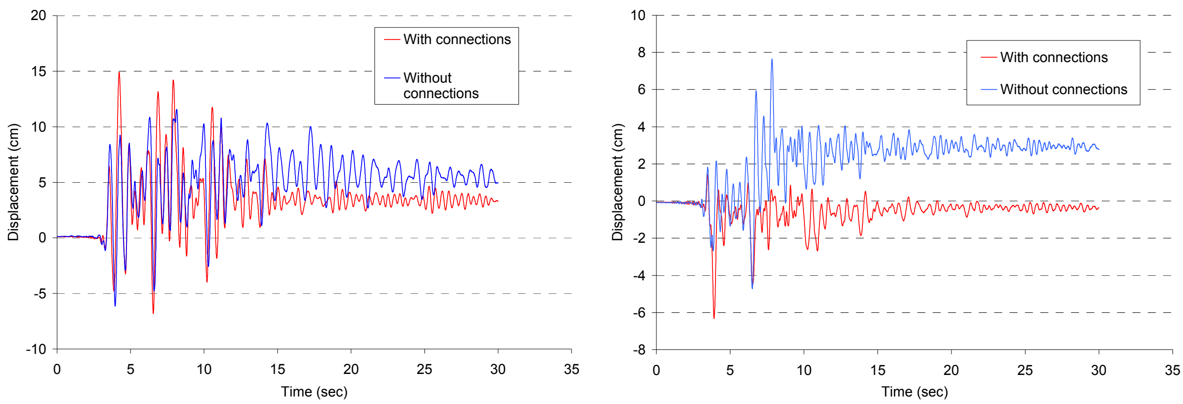


Figure 10: Time histories of the top displacement in the out-of-plane direction at positions C (left) and A (right) of the full-structure model, with and without connections, for the Lefkada earthquake.

Concerning the residual displacements, connections reduce them significantly resulting, in some cases, in values less than one half of the corresponding ones without connections.

6.5 Effect of imperfections

Imperfections were considered only in the simplified sub-assembly model (b) of Figure 2. They consisted of missing stones, blocks of reduced width and corner cut-offs. The results showed that, compared to the corresponding structure without imperfections (Figure 2a), the maximum displacements in the out-of-plane direction during the seismic motion are, in general, larger, while the residual ones are smaller, as shown in Table 8. This behaviour is attributed to the fact that model (b) responds more in rocking and less in sliding in the normal to the wall direction, compared to model (a). This is also evident from the time-histories of the top response for the Lefkada earthquake presented in Figure 11.

It should be noted that commonly encountered imperfections at walls are not as detrimental to the safety against collapse as they are when exist at columns [3], because their effect is less pronounced, as damage is usually diffused on the wall's surface.

	Residual displacement (cm)			Maximum displacement (cm)		
Model	Kalamata	Aigio	Lefkada	Kalamata	Aigio	Lefkada
Without imperfections [model (a)]	3.2	5.7	2.5	13.3	12.6	16.8
With imperfections [model (b)]	0.5	3.2	2.9	13.4	16.1	18.3

Table 8: Top displacements in the out-of-plane direction of the model of Figure 2(a) without imperfections and the one of Figure 2(b) with imperfections.

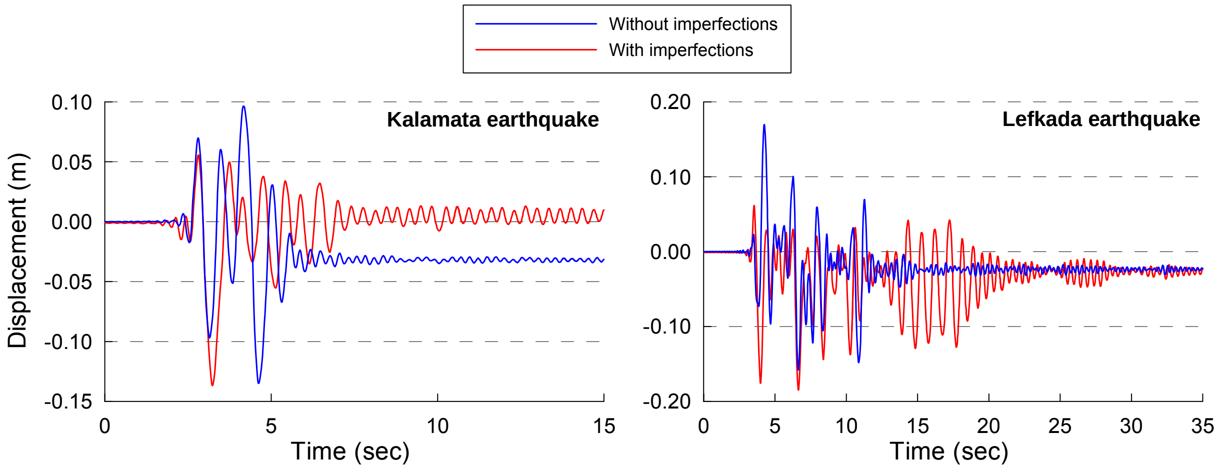


Figure 11: Time histories of the top displacement in the out-of-plane direction of the model of Figure 2(a) without imperfections and of Figure 2(b) with imperfections for the Kalamata and the Lefkada earthquakes.

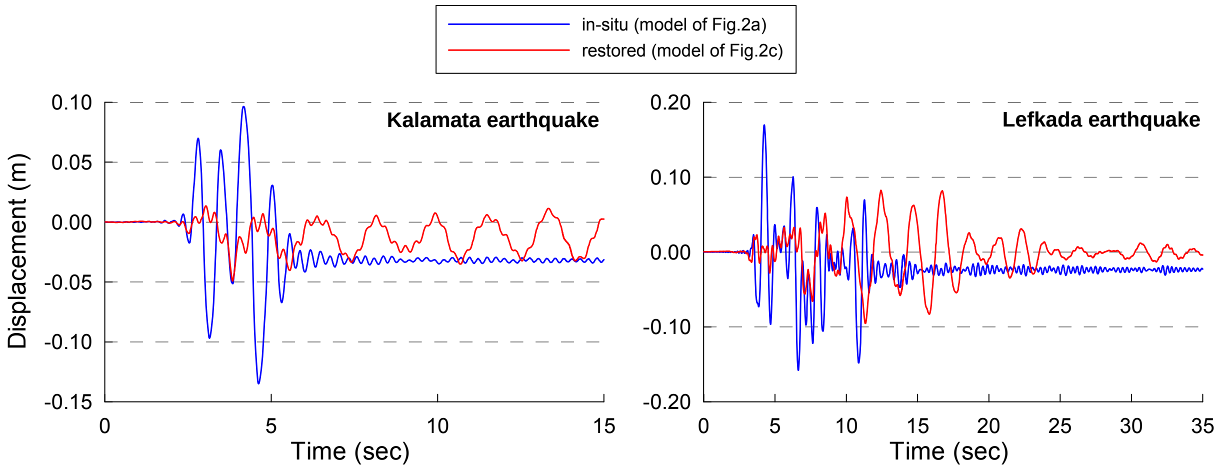


Figure 12: Time histories of the displacement at level of row 7 in the out-of-plane direction of the model of Figure 2(a) (in-situ) and of Figure 2(c) (restored) for the Kalamata and the Lefkada earthquakes.

The reduced height of some sections of the walls, caused by partial collapse, can also be considered as an imperfection. Thus, the effect of restoring the wall to its full height was examined. As can be seen from Figures 7 and 8, this intervention reduces the maximum displacements and the relative slip between adjacent rows of stones. However, the residual displacements are not affected significantly and, in some cases, might be even larger at the restored wall than at the partially collapsed one.

In Figure 12, the time histories of the displacement in the out-of-plane direction at the level of row 7 of the models (a) and (c) of Figure 2 are presented for the Kalamata and the Lefkada earthquakes. Row 7 corresponds to the top of model (a) and to almost the mid-height of model (c). It is evident that the displacements are smaller at the full-height model (c), but rocking is also much more pronounced.

6.6 Collapse mechanism

For strong ground shaking, collapse of some stones might happen. For the seismic motions considered in this analysis, collapse occurred only at the full-structure model and for the Aigio earthquake and concerned the outermost upper row of stones (architraves), which are larger in size than the other stones of the walls. Two snapshots of the collapse of the architraves of the S wall are shown in Figure 13. Note that, for the Aigio record, collapse occurred in both cases, with and without connections.

Similar results were obtained from additional runs with other models of restoration scenarios and other seismic excitations not presenting in this analysis. In all cases, collapse initiated from the architraves of the walls, which seem to be the most vulnerable part of the structure.

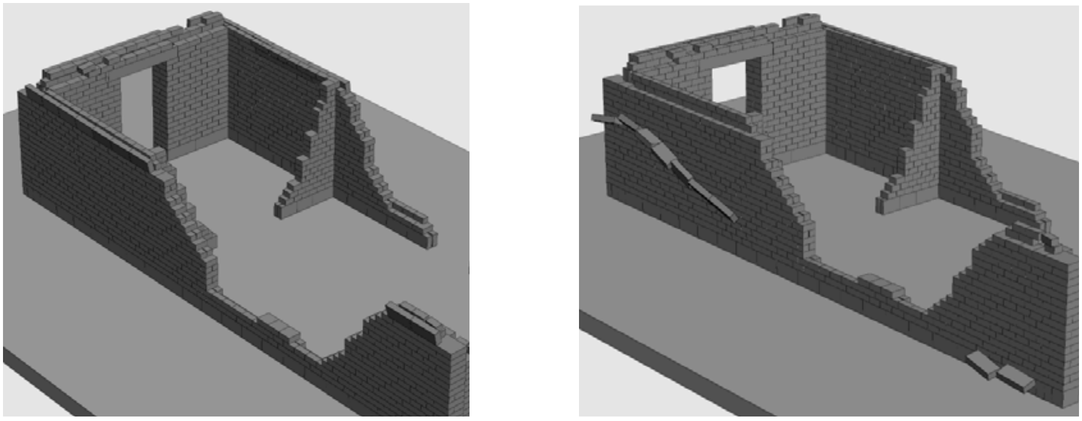


Figure 13: Snapshots of the collapse of the architraves of S wall for the Aigio earthquake.

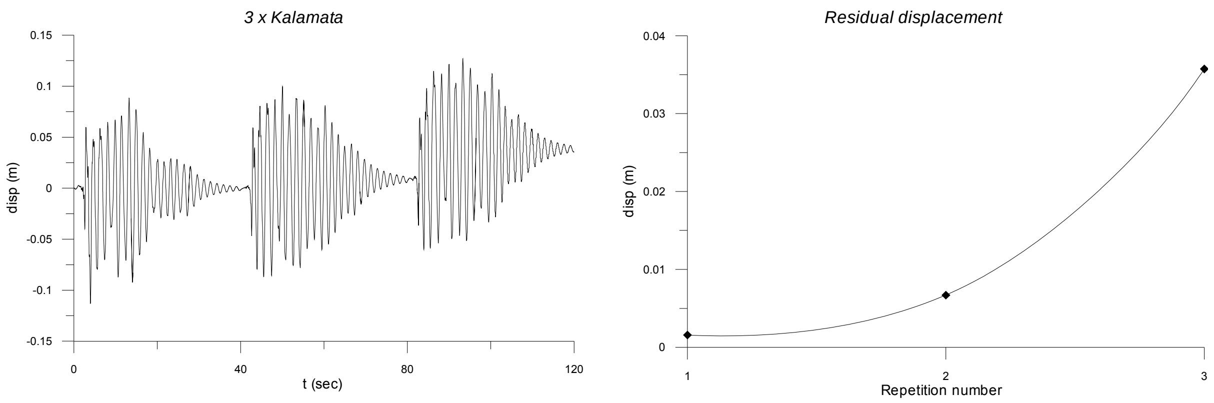
6.7 Effect of the seismic motion characteristics

With the exception of the Athens record, that caused small displacements to the structure, the rest three seismic motions considered in the analyses produced significant deformations, not only during the ground shaking but also residual ones after the end of it.

In general, the displacements were larger for the Lefkada earthquake, which can be attributed to the long duration of this record. In many cases, Lefkada resulted to more than double the displacements caused by the other earthquakes.

Among Aigio and Kalamata records, the Aigio earthquake produced, in general, larger displacements. It should be noted that Aigio contains a strong motion part of smaller duration compared to Kalamata, but with larger peak acceleration. Also, the Aigio record contains a clear, almost sinusoidal pulse with a period of 0.5 sec, which seems that played an important role to the response. It is reminded that, for the full-structure model, collapse of the architrave stones occurred only for the Aigio earthquake.

These results show that the ground motion characteristics influence significantly the response. For classical multi-drum columns, it is known that long-period ground motions are much more destructive than high-frequency ones [1]. However, the response of columns is dominated by the rocking, while for walls, rocking and sliding might be equally important. Thus, conclusions concerning columns cannot be directly applied to walls. Further research is needed on this subject.



(a) (b)

Figure 14: Top displacement in the out-of-plane direction of model of Figure 2(c) for three consecutive applications of the Kalamata earthquake: (a) time history of the response; (b) increase of the residual displacement with the number of repetitions of the ground motion.

The effect of repeated earthquake excitations was also examined for the restored sub-assembly model of Figure 2(c). To this aim, three consecutive ground motions (Kalamata record) were applied to the structure with the residual displacements caused by the previous earthquake being considered as initial conditions for the next one. The results obtained are shown in Figure 14 and show that the residual deformation increases exponentially with the number of repetition of the ground motion. However, this conclusion cannot be generalized, since, due to the nonlinearity of the response, the opposite phenomenon may occur in some cases, i.e. a seismic excitation might reduce the deformation caused by a previous ground motion. This behaviour was observed for classical columns [16].

7 CONCLUSIONS

- Maximum displacements in the in-plane direction of the walls are much smaller than in the out-of-plane direction. However, residual displacements are of similar magnitude.
- The friction coefficient does not influence, practically, the maximum displacements. Its effect to the residual displacements depends on the characteristics of the ground motion.
- The sub-assembly models overestimate the maximum displacements, compared to the full-structure model, because the stiffness offered by the transverse walls is neglected and the structure responds with pronounced rocking. For the full-structure model, sliding seems to be more intense and, for this reason, the residual deformation is, in general, larger compared to the simplified sub-structure models.
- The metallic connections between the stones decrease significantly the residual deformation. However, the maximum displacements might be larger in some cases, because connections result in more intense rocking response, especially at the full-height parts of the walls.
- Imperfections at the blocks due to existing damage result in more intense rocking and less sliding. Thus, the maximum displacements increase, while the residual ones generally decrease.
- Restoration of a partially collapsed part of the wall to its full height reduces the maximum displacements, while the residual displacements are not affected significantly.

- For strong seismic motions, collapse of some parts of the walls might occur. Collapse starts from the architrave stones.
- The characteristics of the base excitation influence significantly the response, but further research is needed on this subject.
- The repetition of the seismic motion might increase significantly the residual deformation produced by previous earthquakes.

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