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DAMAGE ASSESSMENT OF CLASSICAL MONUMENTS USING NONLINEAR DYNAMIC SIMULATIONS

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Abstract

The assessment of the seismic vulnerability of classical monuments is the aim of the present study. For this purpose, nonlinear dynamic analysis using the Discrete Element Method (DEM) was used in order to determine the seismic behavior and estimate the displacement profile for three common structural assemblies that are typically found in classical monuments, such as single columns and colonnades. More specifically, the paper examines the behavior of a column on the Parthenon's Pronaos and two colonnades one forming a straight line and another with a corner arrangement. Nine seismic excitations, specifically chosen for the site of the Athens Acropolis, thus being compatible with geological and tectonic criteria at the site, were applied in one and in two horizontal directions. The dynamic numerical simulations are a non-invasive tool with low computational cost and sufficient accuracy that can be used in order to take measures for cultural heritage preservation.

Keywords: Seismic vulnerability of monuments, Parthenon, dynamic analysis, Discrete Element Method.

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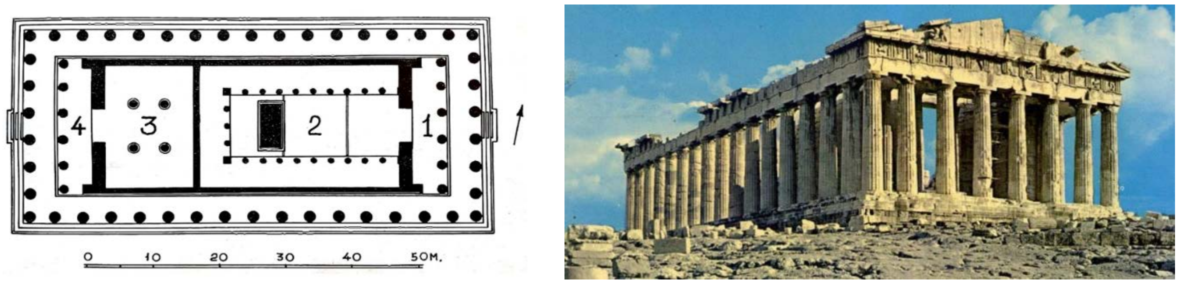
1 INTRODUCTION

Among the monuments perched on the rock of the Acropolis is the temple of the Parthenon. The most imposing building of the ancient Greek world was studied in the context of this work as it is the most important cultural heritage monument of Greece. It is a full-marble temple of Doric style that includes relief fronts, a pavilion with eight columns on the east and west side and seventeen columns on the north and the south side. The inner rectangular core of the temple, the cella, also surrounded by a colonnade, has the form of an amphitheater following the Ionic standards, with columns arranged only along the small sides. There are four spaces in the cloister: the pronaos, the nave, the opisthodromos and the opisthonaos (Figure 1).



(a) (b)

Figure 1: (a) Plan of the Parthenon and numbering of the rooms of the cella: 1 pronaos, 2. nave, 3. opishthodromos, 4. Opishthonaos, (b) northwestern view of the Parthenon.

For a more accurate assessment of the current condition of the Parthenon, it is useful to make a historical review of the existing damage and the factors that led the monument to the condition that it survives in our days. The temple was preserved in its original form until 267 AD, when parts of it were destroyed due to the burning of the temple by the Erulians. In 529, 1205, and 1456 AD the temple was transformed to a Christian church, first a cathedral for the Frankish conquerors and then a mosque for the Turkish invaders, respectively. The most destructive event in the monument's lifetime occurred in 1687 AD by the Venetian army of Morosini, who during their fight against the Turks blew up the building and destroyed large parts of it. In addition to the explosion, damage was caused during the attempt to loot the monument. In a similar attempt in 1801 AD, extensive damage was caused by the sawing and removal of a large number of sculptures by Thomas Bruce [1]. However, in addition to human-induced damage, various mechanisms of deterioration and erosion such as physical, chemical, mechanical, biochemical, and more generally environmental conditions, and seismic events are equally important causes of damage. Over the last decades, extensive restoration works were carried out and are about to be concluded in the near future.

2 SEISMIC RESPONSE OF THE PARTHENON

2.1 Damage due to past earthquakes

Many earthquakes have struck the Parthenon during its long lifetime that spans thousands of years. Three are the major factors that have determined the seismic behavior of the monument: the seismicity of Attica, the composition of the Acropolis rock and the way that the Parthenon was constructed [2,3,4]. There is a consensus among structural engineers, that the structural materials, the structural system and the excellent quality of the marble architectural elements have also given the temple an extraordinary structural capacity.

The most important seismic event that has struck the monument on the Acropolis hill, was the 1981 Alcyonides earthquake. During this earthquake, deformations were observed starting

from the lower drum of the columns up to the thrigos. The modular construction of the monument causes the rocking and sliding of its marble drums during an earthquake, resulting in permanent displacements that threaten its capacity to future seismic events.
The table below (Table 1) summarizes some major historical earthquakes that have struck the Parthenon [1,5]. This summary is attributed to Kalogeras and Egglezos [6] who compilation the listed information, while the peak ground accelerations were calculated according to the ground motion prediction relation of Skarlatoudis *et al.* [7].

Table 1: Major earthquakes that affected the Parthenon monument.

Number	Magnitude (Richter)	Location	Distance (km)	Date	PGA (cm/sec^2)
1	-	Atalanti	140	426 B.C.	-
2	-	Oropos	40	1805	40
3	6.9	Atalanti	100	1894	30
4	6.7	Korinthos	77	1981	30

2.2 Seismic scenaria considered

The study of the seismic history of Athens and the most important earthquakes that have hit the Acropolis is an important step in the assessment of the seismic behavior of the monument. In the present work, accelerograms that are compatible with the seismotectonic environment of the Acropolis area and cover a wide range of frequency content have been selected. The ground motion selection, significantly affects the seismic response of such modular structures, as discussed by Psycharis *et al.* [8]. The ground motion selection was based on the report of Psycharis [9], where it is noted that the influence of the dynamic response of the Acropolis rock on the seismic motion at the top of the hill was taken into account approximately, using the topographic amplification factor of Eurocode 8.

In the seismic hazard study for the Athens area conducted by Ambraseys [10], it was shown that the ground acceleration that can occur with an annual probability of exceeding 5×10^{-5} is about 0.19g. This acceleration corresponds to strong earthquake, but, usually, is not strong enough to collapse the monument.

Considering parameters that have a decisive impact on the dynamic response of ancient monuments, are the maximum ground velocity and the predominant period of the ground motion as well as directivity effects in the case of proximity to active seismic faults. Nine seismic excitations of surface earthquakes of normal faults were selected from the European and NGA Strong Motion Strong Motion Data Base. The ground motions have moment magnitudes in the range: $5.9 < M_w < 7.0$ and have been recorded in bedrock or rocky/stiff soil.

Table 2 summarizes the characteristics of the nine seismic excitations selected. The table includes the recording of the 1999 Athens earthquake at the Syntagma Metro Station, that was recorded at a distance less than 1km from the Acropolis hill. Also, among the two signals recorded at the Metro Station of Syntagma, recording B was chosen. This signal was recorded at a depth of 11 km and is considered that it has not been affected by the dynamic response of the station building, as opposed to the other recording at the same site (recording A).

Although in the case of the Acropolis hill there are no indications of seismic faults at a distance of up to 10 km, in the selection of the accelerograms for the analyses of the Acropolis monuments, seismic movements recorded at shorter distances from the fault (Cascia and Bagnoli-Irpino records) were taken into account. This selection was due to the estimate that similar ground motions with strong directivity effects can occur in Athens due to historical earthquakes that were caused by faults located at distances greater than 10 km and contained directivity pulses.

Table 2: Seismic ground motions selected.

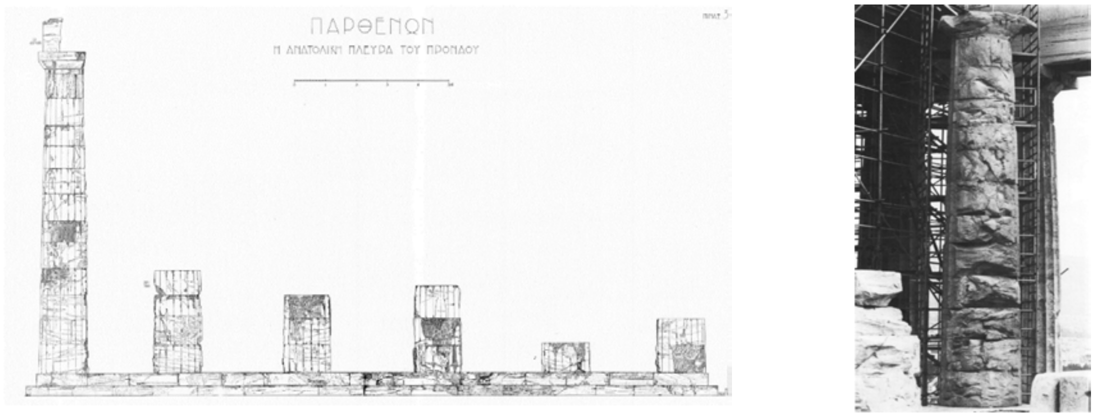
A/A	Moment Magnitude M_w	Location	Epicentral Distance (km)	Date	PGA (g)
1	5.9	Valnerina, Italy - Cascia	1	1979	0.203
2	6.9	Campano Lugano, Italy - Bisaccia	19	1980	0.092
3	6.9	Campano Lugano, Italy – Bagnoli Irpino	6	1980	0.181
4	6.7	Northridge, California, USA – Lake Hughes 9	27	1994	0.217
5	6.7	Northridge, California, USA – San Gabriel E. Grand	42	1994	0.256
6	6.7	Northridge, California, USA – Los Angeles Wonderland Ave.	23	1994	0.172
7	6.5	Kozani, Greece – Kozani Prefecture Blg.	14	1995	0.208
8	6.0	Umbria Marche, Italy – Assisi Stallone	14	1997	0.188
9	5.9	Athens, Greece – Syntagma Metro B	10	1989	0.109

3 DYNAMIC SIMULATIONS

In this study, the simplest assembly of the Parthenon temple was first examined, and two more assemblies have been considered. This simplest assembly was a column of the Pronaos and more specifically the sixth in a row and at full height restored southeastern column. This part of the Parthenon has been severely damaged due to the explosion that occurred in 1687AD. More recent investigations have focused on the identification of the original position of the scattered marble members. In this way, the columns were restored to their original position, but they are of various heights and only the column studied preserves its original height with repositioned drums, reinforced with iron and brass. The column height has been measured and found equal to 10.081 m and the total lower diameter of the drum is equal to 1.649 m. The detailed distribution of the marble drums along the height is shown in detail in Figure 3(b). The structural damage that occurred in this column were primarily thermal fractures in the form of peeling and ruptures. Fractures along the edges due to static and dynamic stresses on the fourth and the sixth drum was also observed. Destruction of surfaces due to the use of heavy tools during looting is also visible, together with fragmentation of the stones with gunpowder. In the ten dislocated drum cracks can be seen due to the swelling of oxidized iron that has been used during the reconstructions. From previous analyses of columns of Pronaos, it has been deducted that the above damage can considerably impair the stability of the column.

The column was first simulated without damage (“intact model”) and then also a model that considers damage (“damaged model”) was created. The geometric data were obtained exclusively from drawings that are available in the literature [11]. The twelve drums of the column were simulated in 3DEC software as “polydrums” with different lower and upper diameters, while the capital was simulated as a single piece. In addition, a rectangular base with dimensions 1.724 × 1.876 m has been placed below the lower drum in order to simulate the solid base on top which the column is standing. Any material losses on the inner side have been ignored and no account has been taken for the fasteners and the seals that were installed during the restorations. The structural system made of drums placed on top of the other, makes the behavior of ancient monuments strongly nonlinear and sensitive even to subtle changes of their geometry or the base movement.

A colonnade that consists of three columns in line arrangement that are connected at their top with an epistyle (architrave) is modelled as shown in Fig. 4 using 3DEC software. The axes of the columns are 4 m apart. In order to exactly model the epistyle as it found in the Parthenon, it is three zones as shown in Figure 5 rather than a simple block; giving a height of 1.35 m, a width of each block equal to the distance between the column axes, i.e., 4m, and thicknesses of 0.426, 0.491 and 0.443m, from the outer to the inner zone of the epistyle, respectively. Initially, the colonnade was simulated as "intact" (without damage) following exactly the same geometry for the three columns, as discussed for the intact single column of the Pronaos, but in this case using "poly prism" command of 3DEC. The same colonnade is also tested in a "damaged" configuration. The central (middle) column is taken to be the SE column of the Pronaos with the damages already discussed, while for the side columns a random damage distribution was assumed but being compatible with the damage of the middle column (Fig.4). Specifically, the 2nd and 7th column drums were considered intact, as well as the rectangular base, while, in the other drums, damage were considered, from 1 to 3 in number, i.e., there are indentations ranging from 0.015 to 0.200 m. The epistyle is always considered intact, i.e., without any damage.

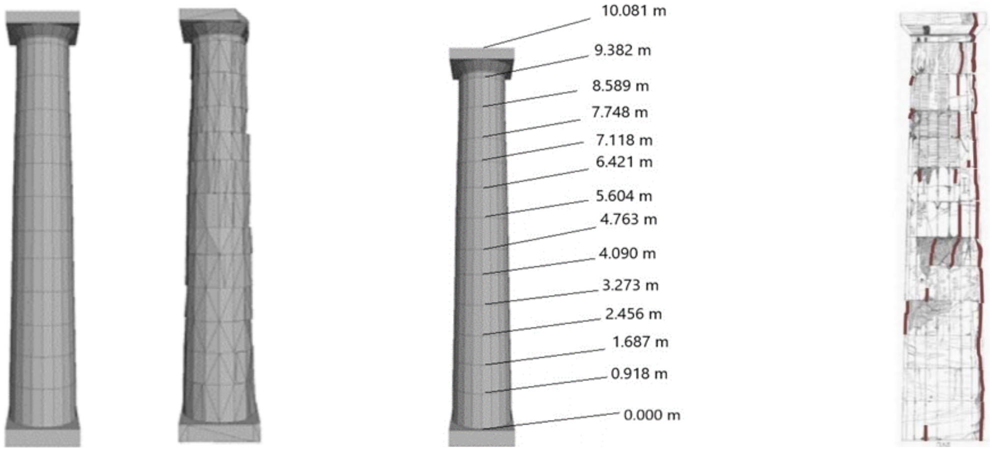


(a) (b)

Figure 2: (a) East side of Pronaos [12], (b) The 6th column of Pronaos [12].

The colonnade assembly was also considered by positioning the three columns in a corner arrangement and the corresponding corner epistyle was modelled as shown in Figs. 7 and 8. The axes of the columns are again 4m apart. The epistyle consists of three zones and the geometry is similar with that of the line arrangement, as shown in Figure 8. Therefore, the height of the epistyle is 1.35 m, the width of each piece such that the composition is achieved, and the thicknesses of the zones are 0.426, 0.491 and 0.443m, from the outer to the inner (Fig. 8). Initially, the colonnade is simulated intact (without damage) following the same geometry for the three columns. The same colonnade is then tested by applying damages. The corner column is taken to be the column of the previous section, with the damages already noted, while for the other two columns a random, same distribution of damages was assumed for both of them, exactly the same as the distribution assumed in the corresponding case of the damaged colonnade in a line arrangement. The epistyle is again considered intact.

Nine seismic scenarios were used in order to investigate the seismic behavior of the columns and the colonnades and to evaluate its deformation along the height under the influence of different seismic intensity records. The seismic excitations were applied in one and two horizontal directions accordingly. More specifically, the N-S direction is considered as the X direction of the model, while the E -W direction is the Y direction of the model.



(a) (b) (c)

Figure 3: (a) Presentation of two models (with and without damage), (b) illustration of the heights of each drum, (c) illustration of a column with damage [11, 12].

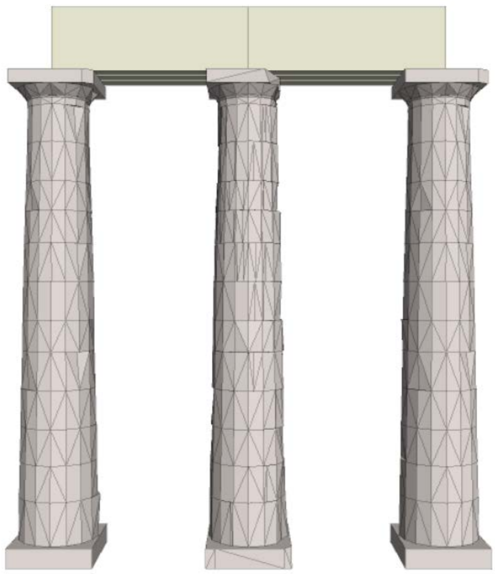


Figure 4: Simulation of the damaged 3-column colonnade in a line arrangement with epistyles (architraves).

(a) (b)

Figure 5: (a) Top view of column drums of the intact 3-column colonnade in a line arrangement; (b) Top view of the 3-zone epistyle of the colonnade in a line arrangement.

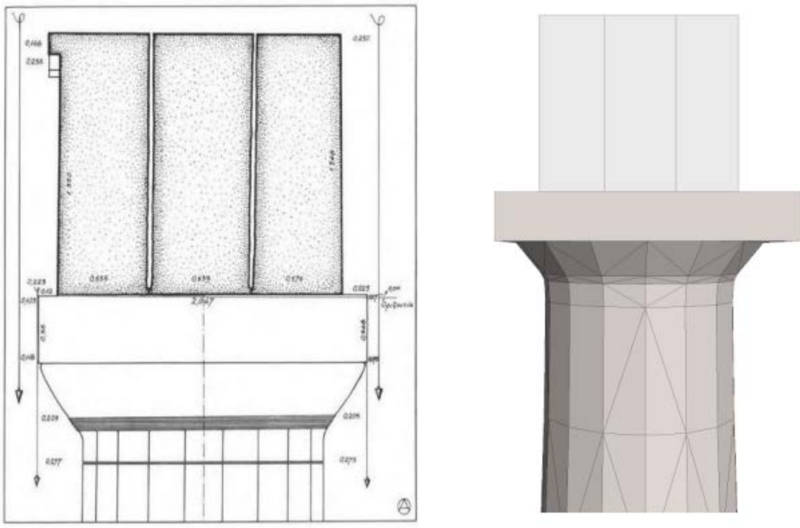


Figure 6: (left) Section of an epistyle of the Parthenon, (right) View of the analogically dimensioned epistyle

To investigate the behavior of the column under seismic excitation and to perform the dynamic analyses, the 3DEC software from ITASCA, which applies the Discrete Element Method (DEM), was adopted. The DEM method is an iterative method that allows calculating the body motions taking into account the interfacial forces at each step of the solution. It is characterized as hybrid as it combines elements of continuous and discontinuous behavior, it is suitable for solving dynamic problems as the bodies are considered as rigid or as deformable pieces interacting at their point of contact, thus allowing shear motion, rotation and detachment. The generalized Mohr-Coulomb model is used in the analysis to simulate the joints. According to reports by Zampas [13], the results of investigating the seismic behavior of columns using 3DEC were satisfactorily verified through experiments at the seismic table of the NTUA, making the program suitable for dynamic analyses of ancient columns despite the complexity and the large sensitivity of such systems.

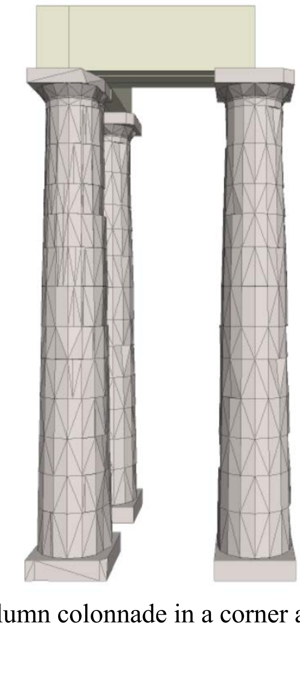
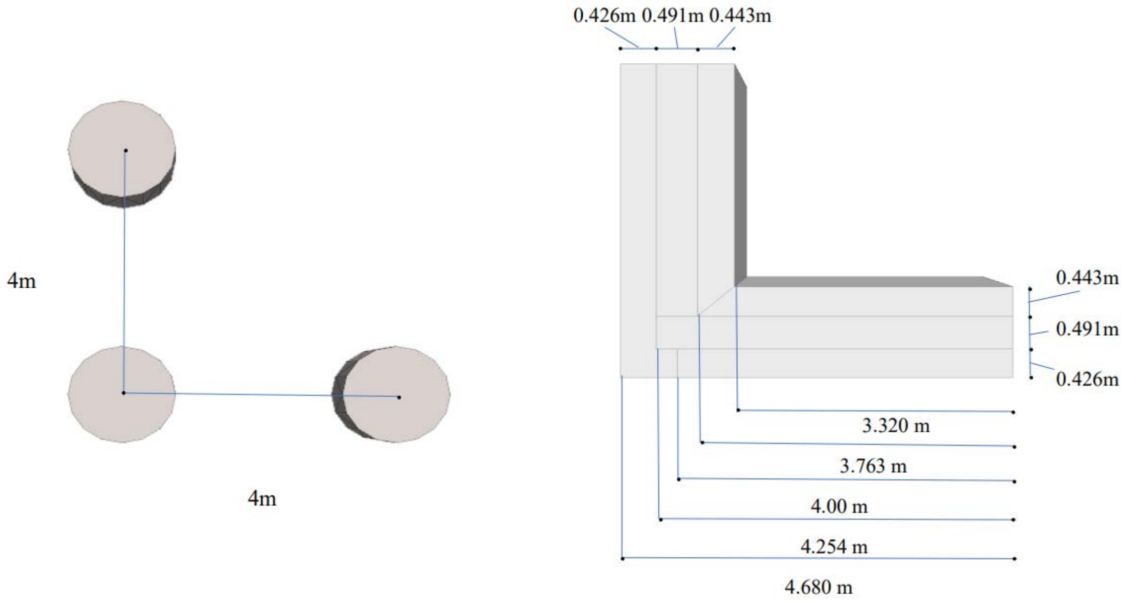


Figure 7: Simulation of the damaged 3-column colonnade in a corner arrangement with epistyles (architraves).



(a) (b)

Figure 8: (a) Top view of column drums of the intact 3-column colonnade in a corner arrangement; (b) Top view of the 3-zone epistyle of the colonnade in a corner arrangement.

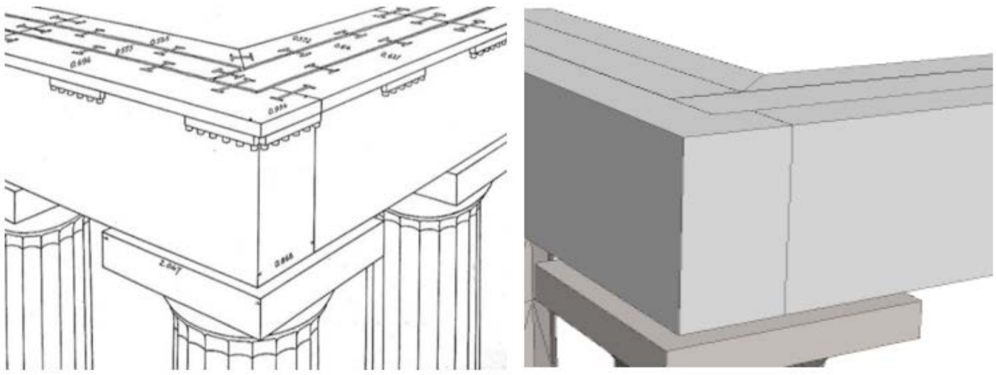


Figure 9: (left) Composition of corner epistyles [14], (right) View of the epistyle.

4 NUMERICAL RESULTS

A total of 108 analyses were performed for two conditions of the assembly considered, i.e. intact and damaged. Furthermore, 18 seismic scenarios were considered, i.e. nine seismic records along the X direction and nine in the X+Y direction. Figure 10 shows the plots of maximum absolute displacement in X and Y axis for the Bagnoli Irpino record applied along the X and X+Y direction for the two models of the single column assembly (intact and damaged) as well as the geometric mean of the displacements in X and Y axis for the two models both for earthquake in X direction and in X+Y direction. From the observation of the diagrams, it becomes evident that larger displacements in both the X and Y axes are presented when the earthquake is applied to the two horizontal axes simultaneously compared to the application of a single horizontal seismic component to the X axis. The higher values of displacements can be seen in the capital of the column both for intact and for damaged model, in both axes and for earthquake in X and in X+Y direction. The intact model displays a sightly worse behaviour in comparison with the damaged model fact that it may confirm that existing damage in some cases can be beneficial for the column response in seismic excitation, depending on the direction of the earthquake.

Figure 11 and 12 show, as in Figure 10, the comparative plots of absolute maximum displacements and the geometric mean for earthquake both in X direction and in X+Y direction of the Bagnoli Irpino record for the central column of the colonnade in line and in corner arrangement respectively. In both figures as in Figure 10 the maximum values of displacement can be spotted at the capital of the studied columns as well as larger values are recorded when the seismic excitation is applied in two horizontal axes simultaneously. In the case of the line arrangement the damaged central columns' behavior is slightly worse in comparison with the intact model while in the corner arrangement as in the case of the single column, the damaged model behavior is better than the intact ones.

The effect of each arrangement is also compared for each condition for the Bagnoli Irpino record (intact or damaged model, for earthquake in X and in X + Y direction, for displacement in X and in Y axis) in Figure 13. In the case of earthquake applied in X axis, the corner column of the colonnade in corner arrangement has the larger displacement values while for the case of the seismic excitation applied in two horizontal axes simultaneously, the single column has the worst behavior. In the second case the existence of epistyles acts beneficially in the seismic response of the colonnade especially for the corner arrangement which has the lower displacement values.

Figures 14 to 16 compare all the seismic scenarios considered for the three assemblies (single column, central column of the colonnade in line and in corner arrangement). More specifically, it provides the mean distribution of the displacements along the height of the column when it is studied as a single column or as part of colonnade in the two arrangements considered. Thus, for the majority of the structural arrangements that are included in classical monuments, it can be estimated the displacement profile in case of a possible earthquake with a non-invasive analytical method. The diagrams of maximum relative displacements in the X direction are presented, their mean value separately marked and subsequently normalized to half the mean diameter of each column drum and then to the maximum value in height of each arrangement both for the intact and the damaged model. For the single column the values of relative displacement are higher both for the intact and the damaged model in comparison with the columns of the two colonnades considered. The capital of the column has the maximum displacement in the case of the single column while in the case of colonnades the maximum relative displacement can be found either among the three lowest drums or among the two highest drums and the capital of the column.

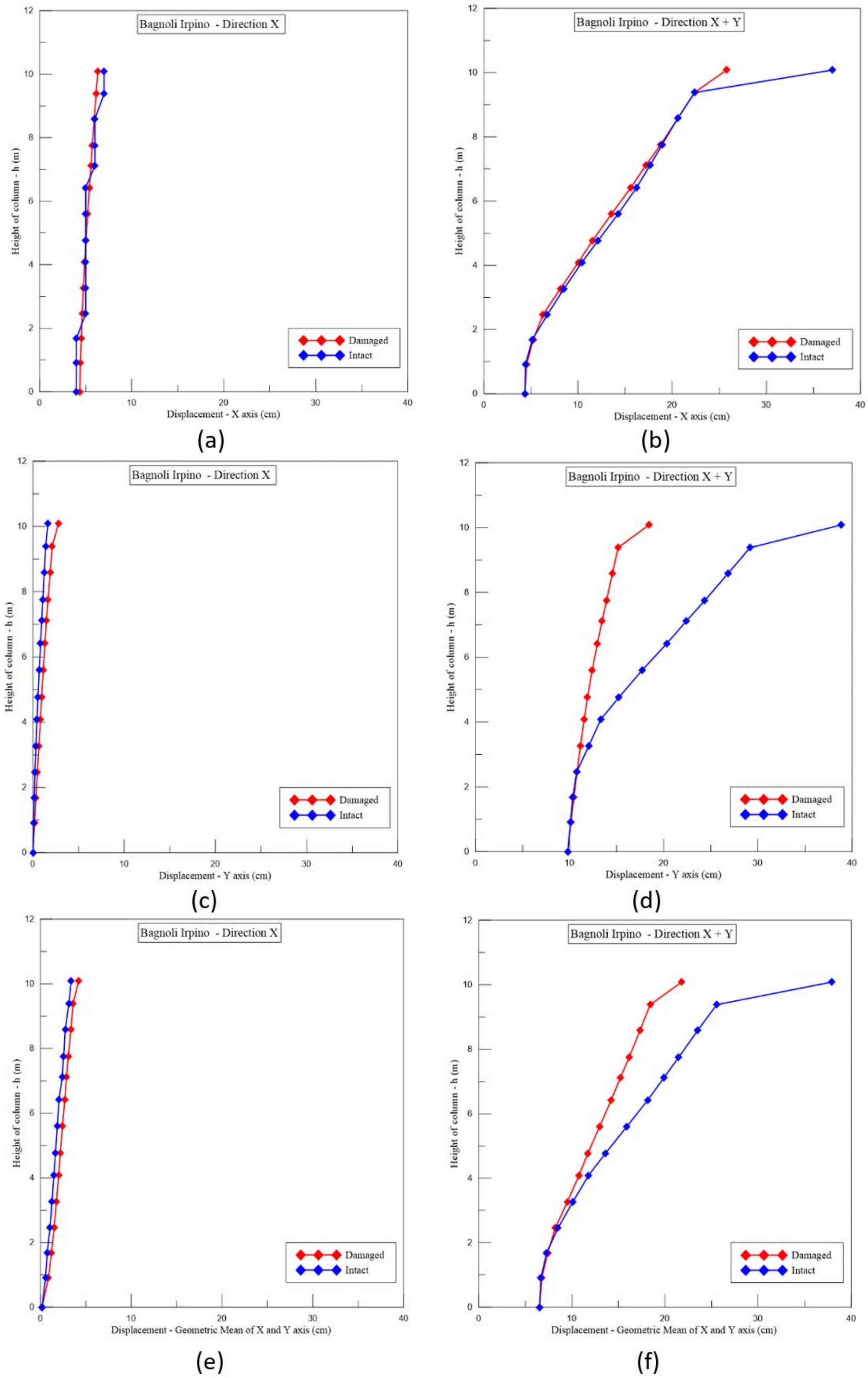


Figure 10: Single column assembly: diagrams of absolute maximum displacement of the Bagnoli Irpino record: (a) X direction displacements, earthquake in X direction, (a) X direction displacements, earthquake in X+Y direction, (c) Y direction displacements, earthquake in X direction, (D) Y direction displacements, earthquake in X+Y direction, (e) geometric mean of displacements, earthquake in X direction, (f) geometric mean of displacements. earthquake in X+Y direction.

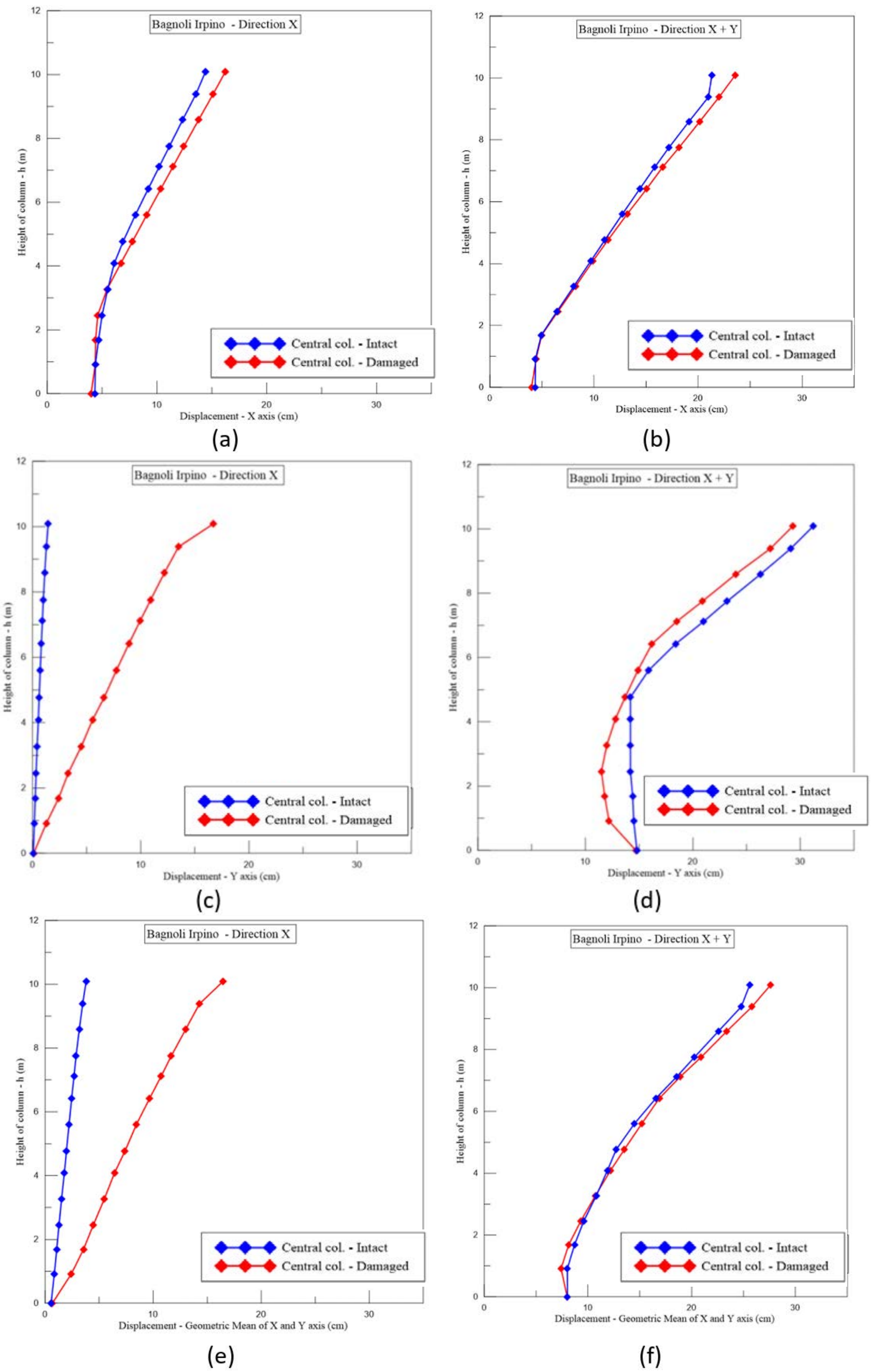


Figure 11: Colonnade in a line arrangement assembly - the central column: diagrams of absolute maximum displacement of the Bagnoli Irpino record: (a) X direction displacements, earthquake in X direction, (a) X direction displacements, earthquake in X+Y direction, (c) Y direction displacements, earthquake in X direction, (D) Y direction displacements, earthquake in X+Y direction, (e) geometric mean of displacements, earthquake in X direction, (f) geometric mean of displacements. earthquake in X+Y direction.

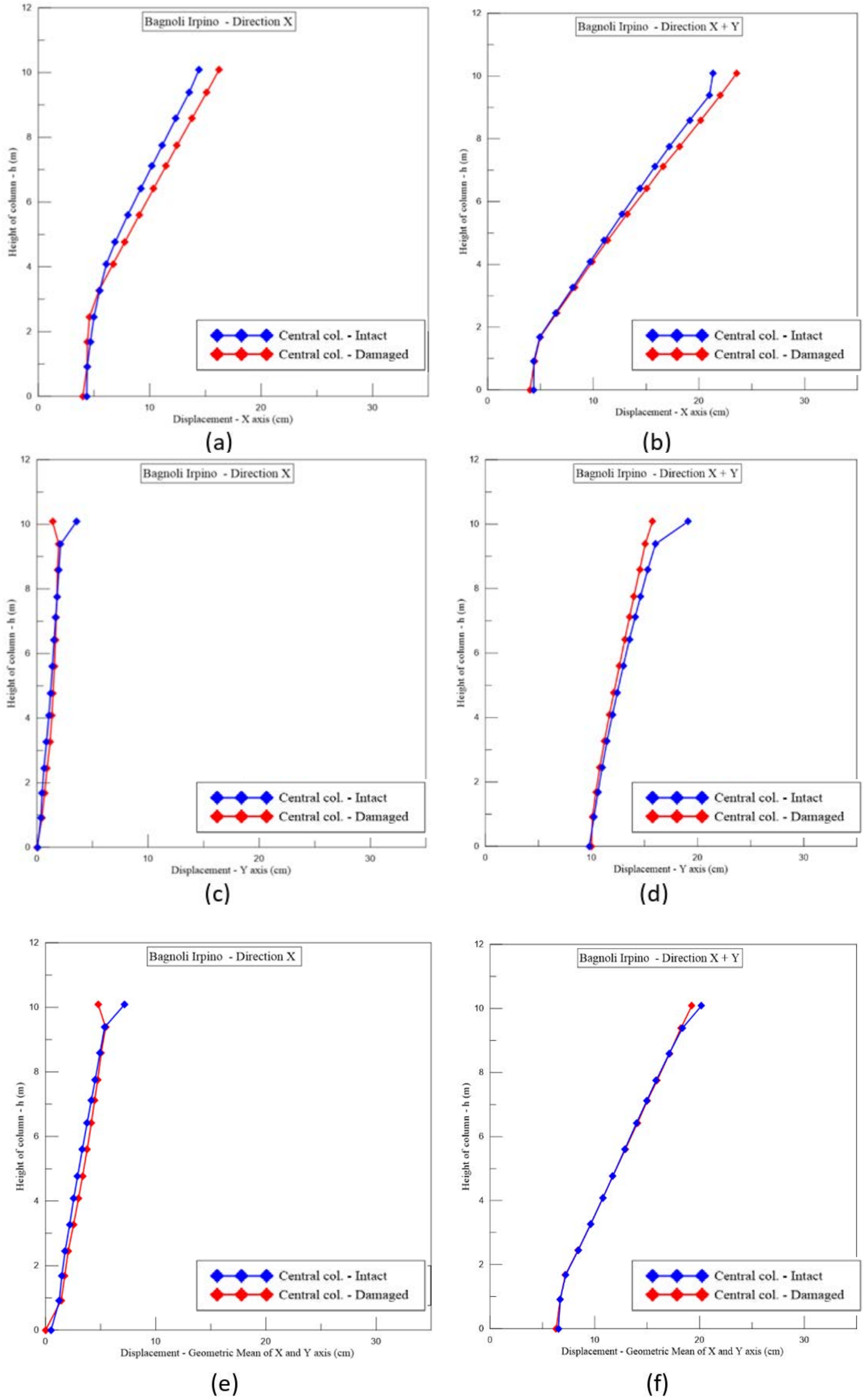


Figure 12: Colonnade in a corner arrangement assembly - the central column: diagrams of absolute maximum displacement of the Bagnoli Irpino record: (a) X direction displacements, earthquake in X direction, (a) X direction displacements, earthquake in X+Y direction, (c) Y direction displacements, earthquake in X direction, (D) Y direction displacements, earthquake in X+Y direction, (e) geometric mean of displacements, earthquake in X direction, (f) geometric mean of displacements. earthquake in X+Y direction.

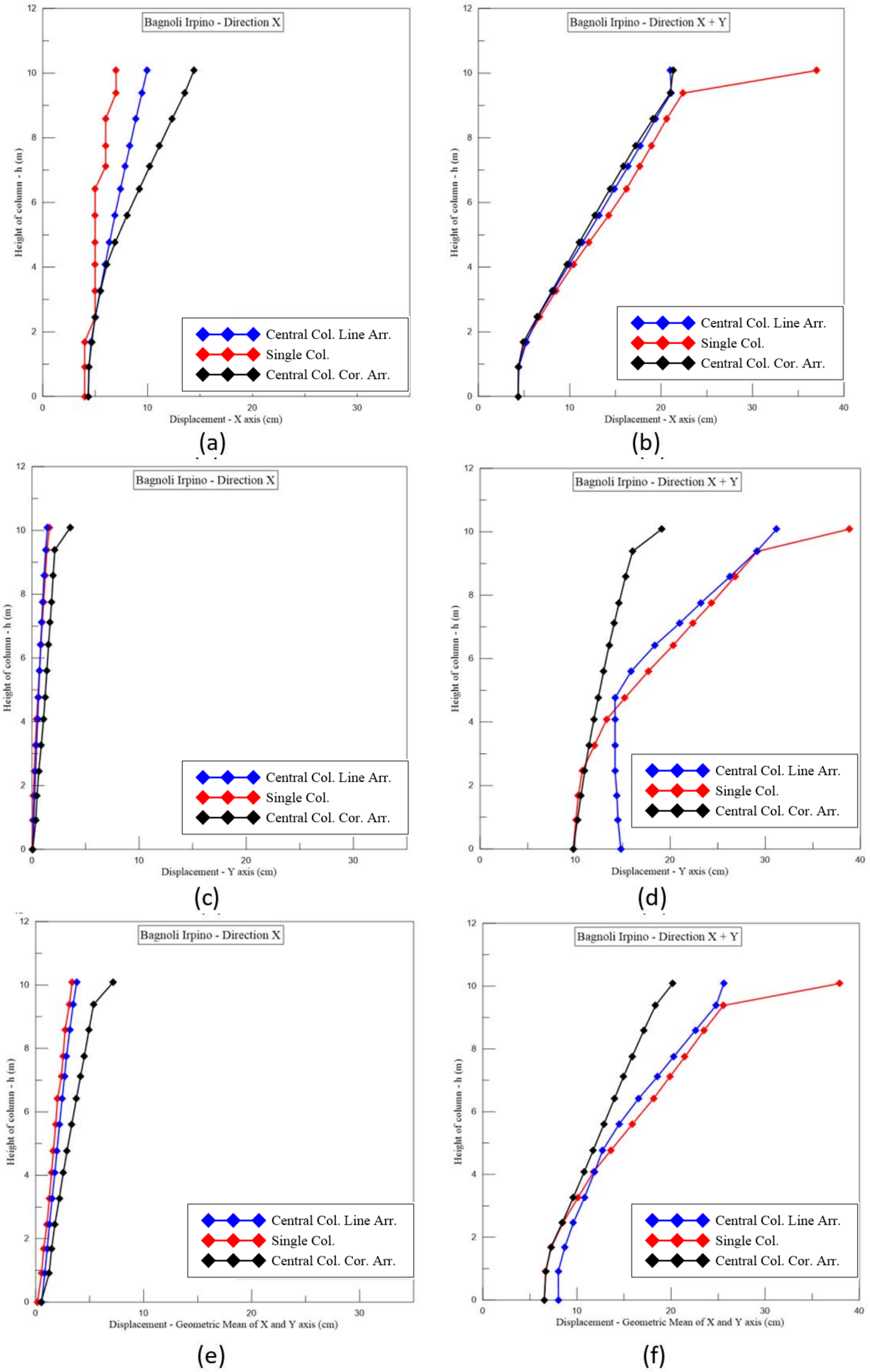


Figure 13: Diagrams of absolute maximum displacement of the Bagnoli Irpino record for single column and for the central column of the colonnades in line and in corner arrangement: (a) X direction displacements, earthquake in X direction, (a) X direction displacements, earthquake in X+Y direction, (c) Y direction displacements, earthquake in X direction, (D) Y direction displacements, earthquake in X+Y direction, (e) geometric mean of displacements, earthquake in X direction, (f) geometric mean of displacements. earthquake in X+Y direction.

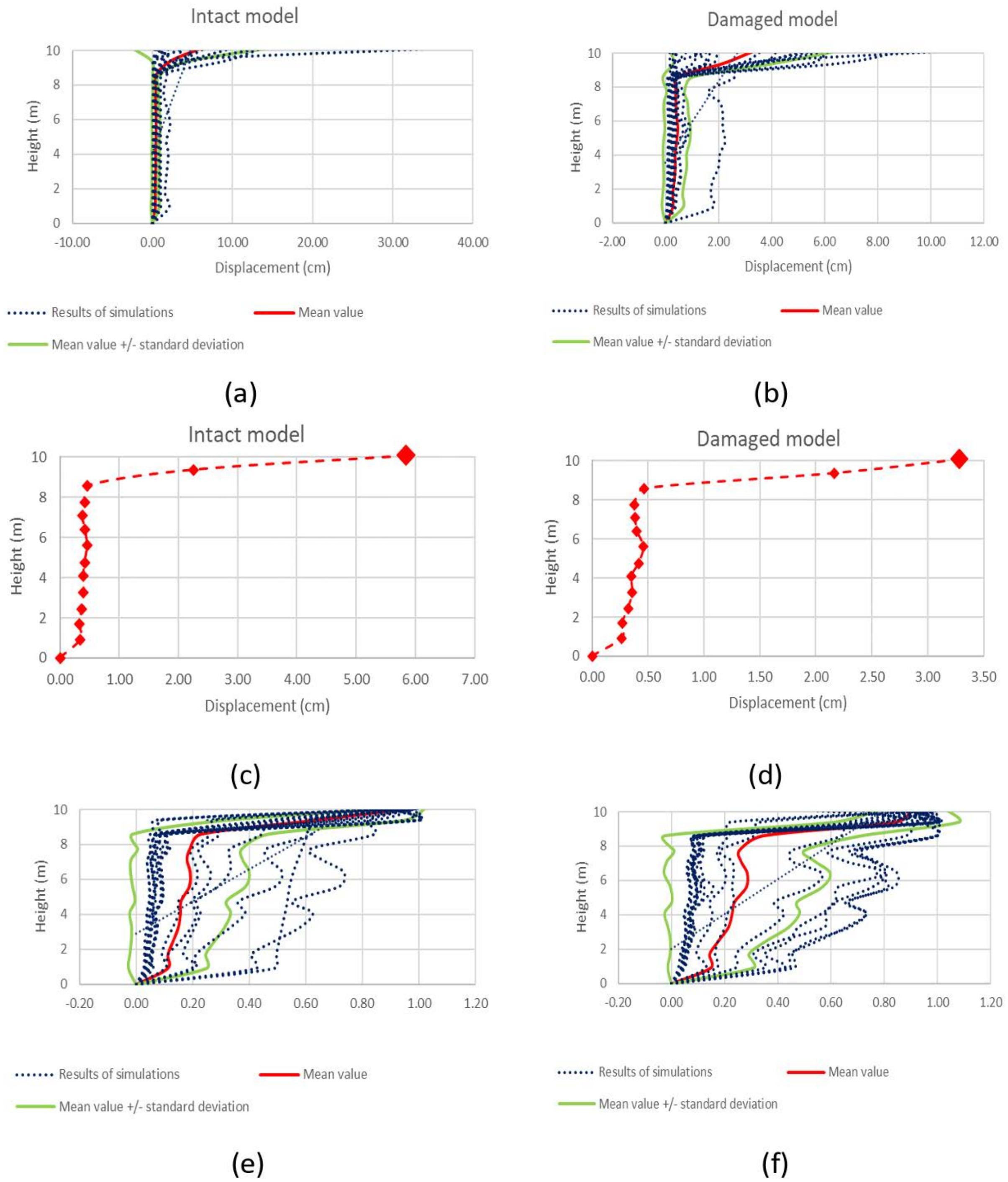


Figure 14: Plots of maximum relative displacements, mean value and standard deviations in X axis for earthquake in X direction from all the analyses of the single column for intact (a) and damaged model (b), only the mean value of intact (c) and damaged model (d) and further the (a) and (b) plots normalized to half the mean diameter of each drum and then to the maximum value in height (e and f respectively).

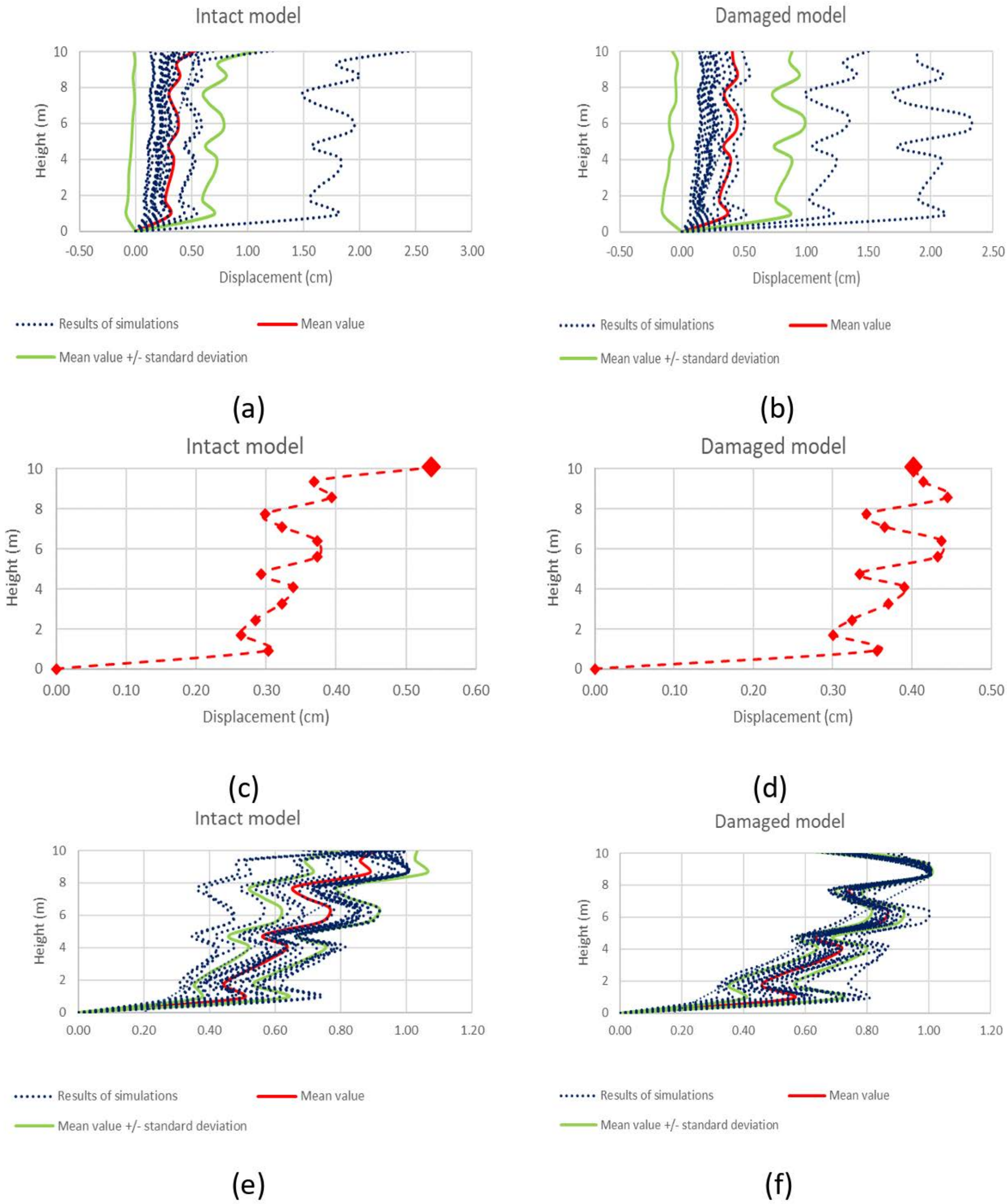


Figure 15: Plots of maximum relative displacements, mean value and standard deviations in X axis for earthquake in X direction from all the analyses of the central column of the colonnade in line arrangement for intact (a) and damaged model (b), only the mean value of intact (c) and damaged model (d) and further the (a) and (b) plots normalized to half the mean diameter of each drum and then to the maximum value in height (e and f respectively).

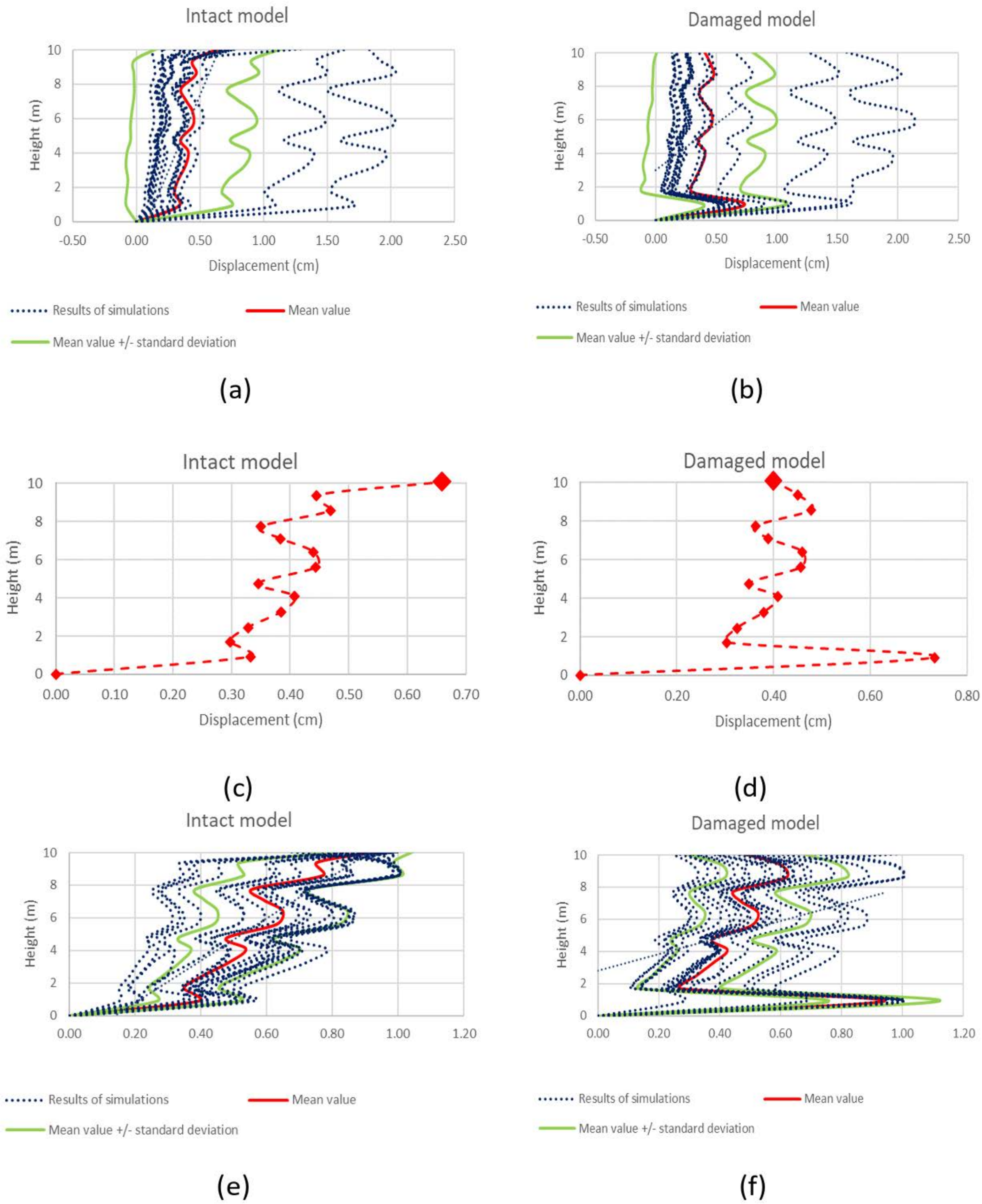


Figure 16: Plots of maximum relative displacements, mean value and standard deviations in X axis for earthquake in X direction from all the analyses of the central column of the colonnade in corner arrangement for intact (a) and damaged model (b), only the mean value of intact (c) and damaged model (d) and further the (a) and (b) plots normalized to half the mean diameter of each drum and then to the maximum value in height (e and f respectively).

5 CONCLUSIONS

Based on the numerical simulations performed, for the representative selected seismic intensities, collapses are very rare, at least for the configurations considered. Therefore, our numerical simulations have confirmed that these structures are characterized by stability. The dynamic simulations where the records are applied simultaneously in the X+Y direction produced the most severe results, in both X and Y direction. By the observation of the absolute maximum X and Y displacements and relative maximum X displacements along the height, it becomes noticeable that the single column shows the maximum (relative) displacement in X (but also in Y) at the column capital. The corresponding column in the colonnade models often show maximum (relative) X-displacements in the 1st drum as well as at intermediate (7th, 8th) ones, in the damaged models, while in the original (intact) models it shows high relative X displacements and higher, e.g., in the capitals, as well.

The damaged models do not show systematically worse behavior compared to the intact ones; on the contrary, they sometime exhibit smaller displacements. Assemblies created by existing damage in the corresponding models may be beneficial for the columns, depending on the direction of the seismic excitation. Larger displacements are observed in the single column, while the other two arrangements show similar behavior with the line arrangement being more vulnerable. The architraves (epistyles) act, in general, as stabilizers. It has been observed that as the size of such structures increases, stability increases [9].

Ground motions with strong directivity effects combined with large earthquake magnitude and duration and long dominants periods, such as the example of the Bagnoli Irpino record, can have a significant impact and cause extremely increased displacements. Another interesting point that arises is that in such cases there are differences in the behavior of the three columns of each arrangement, especially in the Y direction. Thus, variations in kinematic behavior are observed depending on the position of a column in a colonnade.

All in all, special attention should be paid to the geometry and the problem parameters of the analysis due to the significant sensitivity and complexity of the assessment of the seismic vulnerability of classical monuments.

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