Numerical Evaluation of the Seismic Efficiency of Connections of Fractures and Complements of Ancient Colonnades

Maria-Eleni Dasiou, Ioannis N. Psycharis, and Antigone Vrouva

Abstract As a common practice, restoration projects of ancient colonnades have to deal with joining together fragments of architectural members using threaded titanium bars (reinforcement) fixed into place with cement mortar. The basic criterion for the design of such connections is that, in case of a seismic event, the reinforcement should absorb the seismic energy and fail before the marble suffers any damage. For the dimensioning of these connections, the capacity design concept is usually implemented. In this chapter, the efficiency of the reinforcement of the connection calculated with this methodology is investigated for selected severe seismic excitations. The analyses were performed for two case studies with different geometries: a column of the Parthenon Pronaos and the Southern colonnade of the Ancient Agora of Kos in Greece. The induced forces were calculated using the distinct element method. The results show that the design is adequate, as the stresses induced to the reinforcement bars were always less than their ultimate strength and, in many cases, considerably less than their yield resistance as well.

Keywords Restoration of monuments · Design of connections · Fractures · Earthquake performance · Rocking

1 Introduction

Ancient colonnades consist of stone blocks of different sizes and shapes made of marble, stiff limestone or porous stone, depending on the available material in the nearby region. Typically, the blocks are not connected to each other and the structure

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behaves as a system of discrete blocks, except of connectors (clamps and dowels) that are provided in certain places only. In current restoration practice, ancient mortises that are preserved in such places are used to connect the stone blocks with new clamps and dowels made of titanium. The basic principle that is followed for the design of the new connectors is that, in case of a seismic event, the connectors should absorb the seismic energy and fail before the surrounding marble suffers any damage.

Apart from the connectors, the use of titanium bars is also common for joining together fragmented ancient blocks or fragments of blocks with new complements so as to restore the unity of each discrete element of the ancient structure. The principle in designing the bars that are used as reinforcement is that those should bear the induced forces in a seismic event and maintain the discrete block as a whole, while the marble does not suffer any damage.

In general, the design of the restoration anticipates the following sequence of response: The joints between independent blocks are the first to be activated. This does not necessarily imply engagement of the connectors (clamps and dowels), because, typically, there is a gap between them and the mortises of the stones. However, forces are induced to the connections between blocks and new complements. When the movements of the blocks exceed certain values, the clamps and dowels are activated, reducing, in general, the forces applied to the restored interfaces of fracture. After the failure of the connectors (clamps and dowels), it is possible that rehabilitated members of the structure lose their integrity; in that event, the titanium bars of the reinforcement should yield prior to any other damage to the marble.

In order to follow the above-mentioned procedure for the design of the reinforcement of the complements, one should know the forces that will be induced to the connectors and the reinforcement during an earthquake. However, the calculation of these forces is not an easy task, since the response of the structure is governed by rocking and sliding of the individual stone blocks. Previous investigations [1–6] on the dynamic behavior of single freestanding columns and sub-assemblages of ancient temples have pointed out that the response of these discrete structures is highly nonlinear and very sensitive to even small changes in the parameters. Thus, the imposed excitation and the frequency content of the ground motion, the degree of the accuracy of the numerical model concerning the geometry of the structure and the assumptions adopted in the analysis (joint properties, friction coefficient, etc.) may affect significantly the results of even rigorous nonlinear analyses. For this reason, the dynamic analyses of such structures contain an inherent uncertainty and their outcomes should be used with caution.

In practice, simplified analyses are usually applied for the design of the connections that are implemented during interventions. These analyses are based on the capacity design concept, thus they end up with the maximum forces that can be developed theoretically, independently of the earthquake excitation. In this chapter, the efficiency of connections of complements, which have been designed by such methodologies, under strong earthquake excitations, is investigated. For this purpose, nonlinear numerical analyses are performed using the discrete element method and the forces induced to the reinforcements are compared with their strength.

2 Principles of Intervention

2.1 General Philosophy

Restoration projects nowadays follow very specific guidelines in order to ascertain the required quality of the intervention. The main scope is the minimum, yet necessary and sufficient, intervention in the monument's inherent characteristics. Of main importance is the respect for the original building techniques, the original structural system and the original materials. Authenticity is a beyond debate concern and goal of the project, in order to maintain the monument at the best possible status and to minimize the alterations. Additional requirements might be reversibility, meaning the ability to revert the monument to its previous—before the restoration—state, maintenance of the structural function and consistency of the individual architectural members.

The use of new material for the complement of missing parts of structural elements is generally restricted to the absolutely necessary and must be kept in a low proportion compared to the original mate-rial. Such decisions must not be based only on stability issues, but also take under consideration the forms and volumes, the visitor's perception of the monument and aesthetic issues. It should be kept in mind that the main "recipients" of the monuments are their visitors and that the cultural heritage that they carry is not addressed to scholars and connoisseurs only, but mainly to the public.

2.2 Structural Restoration

The term 'structural restoration' signifies the series of interventions that are necessary to ensure the bearing capacity of the structure and of its individual parts. To this end, restoration of the connectors between the structural elements and recomposition of the original geometry of the stone pieces that were retrieved during the excavation by connecting fragments and/or complement of stone elements is deemed necessary in many cases.

In antiquity, the connection elements were made of bronze or iron and were covered with lead, cast in the mortises, which after its congelation offered high insulation to the metallic connectors, protecting them from the oxidization and the corrosion. At the same time, the connectors, being ductile materials, contributed to the overall behavior of the structure in case of an earthquake. Two types of connectors were used: dowels, which connected elements between consequent layers along the height and resisted the shear forces; and clamps, which connected stones belonging to the same layer and prevented their relative dislocation through their tensile resistance. In the ultimate limit state, the dowels and the clamps were meant to fail before the failure of the stone.

In many restorations realized in the 19th ant the 20th century, the structural steel that was used in typical constructions was applied also to monuments for the enhancement of their bearing capacity and for the connection of fragments of architectural members. The steel elements were usually cast in lead, as a follow up of the ancient practice. Cement mortars were widely used for covering mass lacks. This technique caused significant damage to the monuments, because the cast lead failed to reassure the same impermeability as the ancient one and environmental actions, due to their intense corrosive character, led to iron's oxidization and subsequently to fracture of the architectural members.

In modern restoration projects, mostly inorganic materials are adopted, in order not to provoke any additional problems in the long term. Thus, for the connections between restored members of the monument (clamps and dowels), specially formed titanium sheets are commonly used, fixed in place with the use of inorganic mortars. Similarly, for joining together fragments and/or complements, threaded titanium bars are applied.

2.3 Design of the Connections

The ancient and the new pieces are typically connected with titanium threaded bars that are inserted in properly drilled holes and fixed into place by mortar. Mortar is also used as the bonding material at the interface of the fraction. As mentioned above, a proper dimensioning of the reinforcement would require difficult nonlinear analyses, which are seldom performed in practice. Usually, analyses based on the capacity design concept are performed [7, 8], which lead to the required reinforcement for resisting the maximum forces that can be induced, without restoring completely the strength of the original material. In example, the design of the connection of fractured architraves is based on the assumption that the architrave is subjected mainly to bending under increased gravity loads by a factor about 1.50; for the connection of fragments at column drums, the required reinforcement is calculated from equilibrium conditions of the complement piece under capacity actions that include the friction forces, assuming that sliding occurs at the joint, and the ultimate resistance of any existing dowels.

3 Case Studies—Description of the Monuments

3.1 Parthenon Pronaos

The first case study concerns the restored part of the Parthenon's Pronaos, situated in the Athenian Acropolis, namely part of the prostyle (prostylon).

The structural system of the ancient temple is well known and thoroughly investigated by scholars and restorers that have studied the monument (e.g. [9]). All the blocks were of white marble derived from the Penteli quarry. The columns were of Doric style with fluting. The prostyle had 6 columns of 12 drums each of uneven height, a capital and a three part architrave (epistyle) and bore a frieze and cornice. The connection with the walls of the main cella was realized at the level of the architraves.

The prostyle suffered extend damages due to the historical fire when the Eruli set fire to the temple and a large part of it collapsed at the bombardment during the Turkish-Venetian war. Alterations in its original structural scheme were made in various historical in-stances throughout the centuries. The former restorers stripped the monument of the additions and structural alterations that did not be-long to the original ancient plan.

In situ were preserved the first column in height of 2 drums, the second in height of only one, the third and fourth in height of 3 drums, the fifth in height of 4 drums and the sixth was complete bearing also its capital. It was decided that since a large part of the column drums rested on the ground and had been attributed to that part of the monument (22 drums and 4 capitals) a restoration was to be carried out [10, 11]. More specifically the first and second column was to be restored to the height of the 6th drum, the third to the 8th drum whereas the fourth and fifth to their full height and their capitals so as to reassemble two blocks of the fifth architrave and one of the fourth.

The columns had a base diameter of 0.82 m. The axial distance between the columns was approximately 3.6 m for the sixth and fifth and 4.2 m for the fifth and fourth and their overall height 9.39 m. The diameter of the capital was 0.625 m and its height 0.69 m, while the abacus had plan dimensions 1.65 m $\times$ 1.65 m and height equal to 0.35 m.

In the analyses presented in this chapter, a full column with its capital is used.

3.2 Part of the Southern Arcade (Stoa) of the Ancient Agora in the Island of Kos

The second case study is based on the part of the southern Arcade (Stoa) of the Ancient Agora in the island of Kos in Greece that has been proposed to be restored. The monument is situated in the center of the modern city of Kos.

An unexpectedly large number of structural members were found in situ. The location where the members were found and the study of the mortises of the connectors confirmed that they derived from specific parts of the building. Thus, the 'erection' of a small part of the Stoa was proposed, using a significant portion of the found ancient members.

The restoration project concerns three columns of the Stoa with the respective parts of the crepis and the entablature (Fig. 1). In this restoration, 37 from the 62 ancient members are to be used. In addition, seven new blocks are to be used to ensure the stability of the structure and, also, for aesthetic reasons.

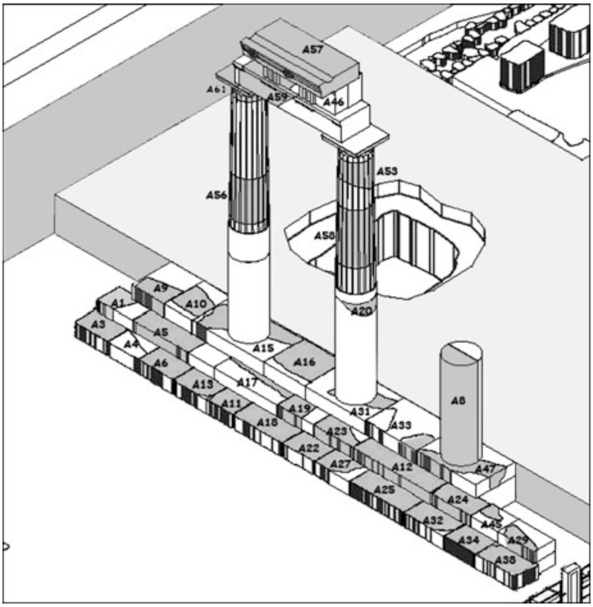


Fig. 1 Drawing of the restoration proposal. The ancient members and fragments are shown in *gray* and the members and complements that will be made of new marble are shown in *white*

The original structure rested on a two-layer base of height 0.55 m, made of porous blocks that lied under the crepidoma (crepis). The crepis consisted of two steps and the stylobate. The first step had height 0.33 m and was made of gray limestone blocks of varying plan dimensions (their length was varying from 0.60 to 1.40 m and their width from 0.50 to 0.70 m). The second step had height 0.29 m and was made of marble blocks of the same overall dimensions. The stylobate was made of marble blocks of height 0.30 m, width about 1.00 m and varying length.

The marble columns of the Stoa were of Doric style without fluting at their lower part, up to a height of 2.07 m. The columns consisted of four drums of uneven height with base diameter 0.78 m. The axial distance between the columns was 2.66 m and their overall height was 5.61 m. The diameter of the capital was 0.635 m and its height was 0.38 m, approximately, while the abacus had plan dimensions 0.85 m $\times$ 0.85 m and height equal to 0.11 m.

The architraves consisted of single blocks, 2.66 m in length, 0.71 m in width and 0.47 m in height. The frieze was made of blocks 1.73 m in length and 0.59 m in height that included two triglyphs and two metopes. Those blocks were either single of full width ($\sim$0.47 m) or were supplemented by other blocks of approximately the same dimensions that completed the width of the layer; the latter is the case of the part of the structure that is considered in this analysis. The cornice had height 0.42 m and was projecting 0.325 m. The block that will be used in the restoration is 1.95 m long.

4 Numerical Analysis

4.1 General

The structural and the dynamic analysis of ancient temples or sub-assemblages of ancient temples differ significantly from the analysis carried out for modern structures, mainly because of their articulate construction. During a seismic event, rocking and/or sliding of the stones, independently or in groups, may occur, which results in highly nonlinear behavior [1–6]. Additionally, the response is very sensitive to the details of the geometry, the characteristics of the ground motion and the joint parameters.

The complexity and the special character of the response of the structure (rocking and sliding) create computational requirements hard to meet with the incorporation of conventional software. For the numerical analyses presented herein, the code 3DEC by Itasca Consulting Group, Inc. [12] was employed, which is based on the discrete element method. The code is designed to allow significant displacements and rotations of the blocks, even total detachment. During the calculation process, the code locates the contacts between the blocks and computes the motion of each block from the forces (normal and shear) that are developed at the joints. The contacts are divided in sub-surfaces, while various types of contact are considered (apex to apex, apex to edge etc.). In this way, rocking and sliding are accurately addressed.

The code 3DEC has been verified and calibrated for the response of ancient colonnades through comparisons of the numerical results with experimental data obtained from shaking table tests performed at the Laboratory for Earthquake Engineering of the National Technical University of Athens [2, 4–6].

4.2 Numerical Model

Although the numerical models used in the analyses were based on the actual restoration proposals, the investigation presented herein is not meant to be applicable only to the specific cases but to evaluate the design procedure in general. The case studies were selected as typical examples, but with considerable differences in their dimensions, being thus representative of many monuments. For this reason, in the case of the column of the Parthenon fictitious complements were considered in three drums (one at the top, one at the middle and one at the base of the column) in an attempt to cover all possible situation that can be encountered in practice.

The connections between the ancient fragments and the new complements were assumed from titanium bars and were designed according to the above-mentioned methodology. The exact geometry and dimensions of the reinforcement were implemented in the numerical models (Figs. 2a and 2b).

The mortar typically used at the interfaces of the connected blocks was not considered, because its actual mechanical properties cannot be precisely defined. In addition, the dowels and the clamps were not included in the numerical model, because

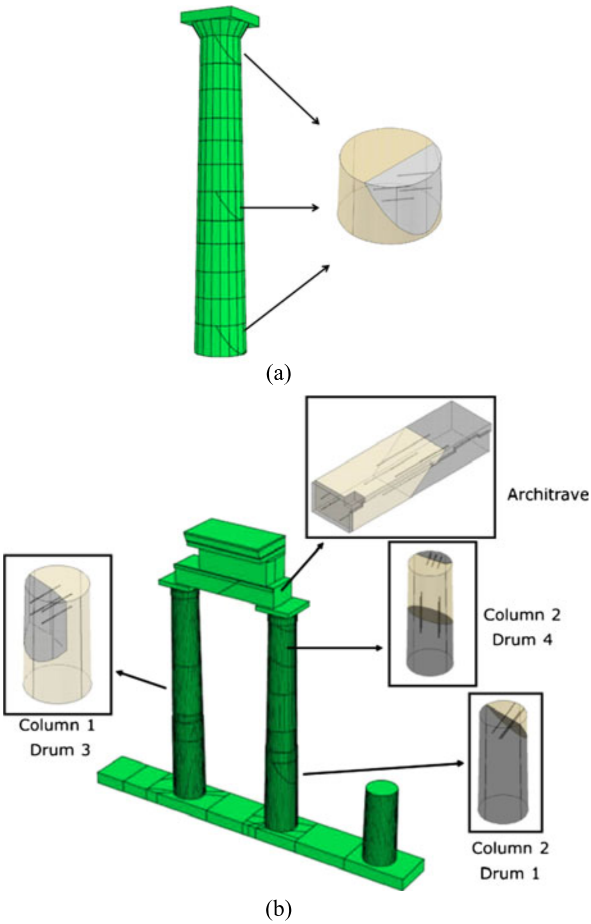


Fig. 2 Numerical model of (**a**) the column of Parthenon Pronaos and (**b**) the part of the southern Arcade of the Ancient Agora [Kos] used in the analyses with 3DEC. Details of the connections considered in the model are also shown

sliding can occur before these connectors are activated, since a gap of 1 to 2 cm, not filled with mortar, is commonly left between them and the edge of the mortises. Both assumptions are to the safety side and lead to the upper limit of the forces that can be induced to the reinforcement.

The analyses were performed assuming that all the structural elements are rigid blocks. The joint properties used in the model were based on former studies [2, 4–6]: the joint stiffness was equal to 5×109 Pa/m in the normal direction and 1×109 Pa/m in the tangential direction while the friction coefficient was taken equal to 0.75. A 10 % mass-proportional damping at $f = 0.3$ Hz was also considered.

The reinforcement (titanium bars) were simulated as nonlinear springs for which the elastic stiffness, the yield force and the ultimate strain were assigned in both the axial and the shear directions. Since pullout test results were not available, the following theoretical expressions, given in [13] and proposed by 3DEC [12], were used to estimate the axial stiffness, K_a and the shear stiffness, K_s:

$$K_a = \pi \cdot k \cdot d_1 \tag{1}$$

$$K_s = E_b \cdot I \cdot \beta^3 \tag{2}$$

where d_1 is the diameter of the reinforcement; E_b is the Young's modulus of the reinforcement material; and

$$k = \left[\frac{1}{2} \cdot G_g \cdot E_b / (d_2/d_1 - 1) \right]^{1/2} \tag{3}$$

in which G_g is the shear modulus of the grout; d_2 is the diameter of the hole; I is the second moment of area of the reinforcement element; and $\beta = [K/(4 \cdot E_b \cdot I)]^{1/4}$ with $K = 2 \cdot E_g/(d_2/d_1 - 1)$.

The ultimate axial strength, P_{ult}, and the shear strength, $F_{s,b}^{\max}$, of the titanium bars were calculated using the formulas proposed in [14] and [15], respectively, and adopted by 3DEC [12]:

$$P_{\mathrm{ult}} = 0.1 \cdot \sigma_c \cdot \pi \cdot d_2 \cdot L \tag{4}$$

$$F_{s,b}^{\max} = 0.67 \cdot d_1^2 \cdot (\sigma_b \cdot \sigma_c)^{1/2} \tag{5}$$

where σ_c is the uniaxial compression strength of the marble (up to a maximum value of 42 MPa); L is the bond length; and σ_b is the yield strength of the reinforcement.

4.3 Seismic Input

As mentioned above, the case studies are used as examples of typical monuments and the analyses aim at investigating the effectiveness of connections in general. For this reason, the earthquake excitations were selected to cover a wide range of recorded ground motions with different characteristics, not necessarily representative of the specific sites of the considered monuments. Ten earthquake records were selected from the strong motion data bases: Cosmos Virtual Center; Pacific Earthquake Engineering Research Center (PEER); European Strong-Motion Database (ESD); National Observatory of Athens; Institute of Technical Seismology and Earthquake Resistant Structures (ITSAK), which had different frequency characteristics. Both horizontal components of each earthquake were applied as the base excitation. The selected earthquakes and their characteristics are shown in Table 1. In Fig. 3, the time-histories of the acceleration of the components that were applied in the transverse direction are shown. The response spectra of both horizontal components are presented in Fig. 4.

5 Results

For all the titanium bars that were used in the connections, the time histories of the axial and the shear forces were obtained from the analyses. Indicative results are

Table 1 Peak ground accelerations in the two horizontal components of the earthquake records considered in the analyses

Earthquake	PGA (g)	
	Longitudinal direction	Transverse direction
Imperial Valley, 1979	0.33	0.25
Lefkada, 2003	0.34	0.42
Aigio, 1995	0.49	0.53
Athens, 1999	0.15	0.23
Kalamata, 1986	0.24	0.27
Erzincan, 1992	0.51	0.25
Gazli, 1984	0.71	0.60
Irpinia, 1980	0.36	0.25
Landers, 1992	0.15	0.17
Northridge [Sylmar], 1994	0.84	0.60

shown in Fig. 5, where the time-histories of the axial force of the four reinforcement bars that were used to connect the two fragmented pieces of the architrave beam of the colonnade in Kos (Fig. 2b) are depicted.

From these results, the efficiency factor for each bar was derived as the ratio of the maximum uniaxial stress, $\sigma_{M,\max}$, that was developed during each earthquake motion over the yield stress, σ_y. The uniaxial stress was calculated using the Von Misses yield criterion:

$$\sigma_M = \sqrt{\sigma^2 + 3 \cdot \tau^2} \tag{6}$$

where σ is the axial stress of the bar and τ is the shear stress. The yield stress σ_y and ultimate stress σ_u of the threaded titanium bars were taken equal to 330 MPa and 420 MPa, respectively.

From the analyses performed, it was found that collapse of the colonnade of the Ancient Agora of Kos occurs for four of the selected earthquakes, namely: Northridge, Irpinia, Erzincan and Gazli. The collapse mechanism for the Sylmar record of the Northridge earthquake is shown in Fig. 6. Since the main scope of this re-search was to evaluate the efficiency of the design of the reinforcement of the connections assuming that collapse does not occur, these records were not further examined for the case study of the monument in Kos.

For the remaining earthquakes, the accomplished efficiency factors of each of the four reinforcement bars that were applied at the connection of the architrave of the colonnade of the Ancient Agora are shown in Fig. 7. None of the bars reached its yield strength for the earthquakes examined.

The two lower reinforcement bars (No. 1 and 2), which were in tension under gravity loads, showed an efficiency factor about 0.60, and were not much affected by the base motion. This value is close to $1/\gamma_G$, where $\gamma_G = 1.5$ is the safety factor for the gravity loads that was used for the design of these reinforcements according to the methodology described above.

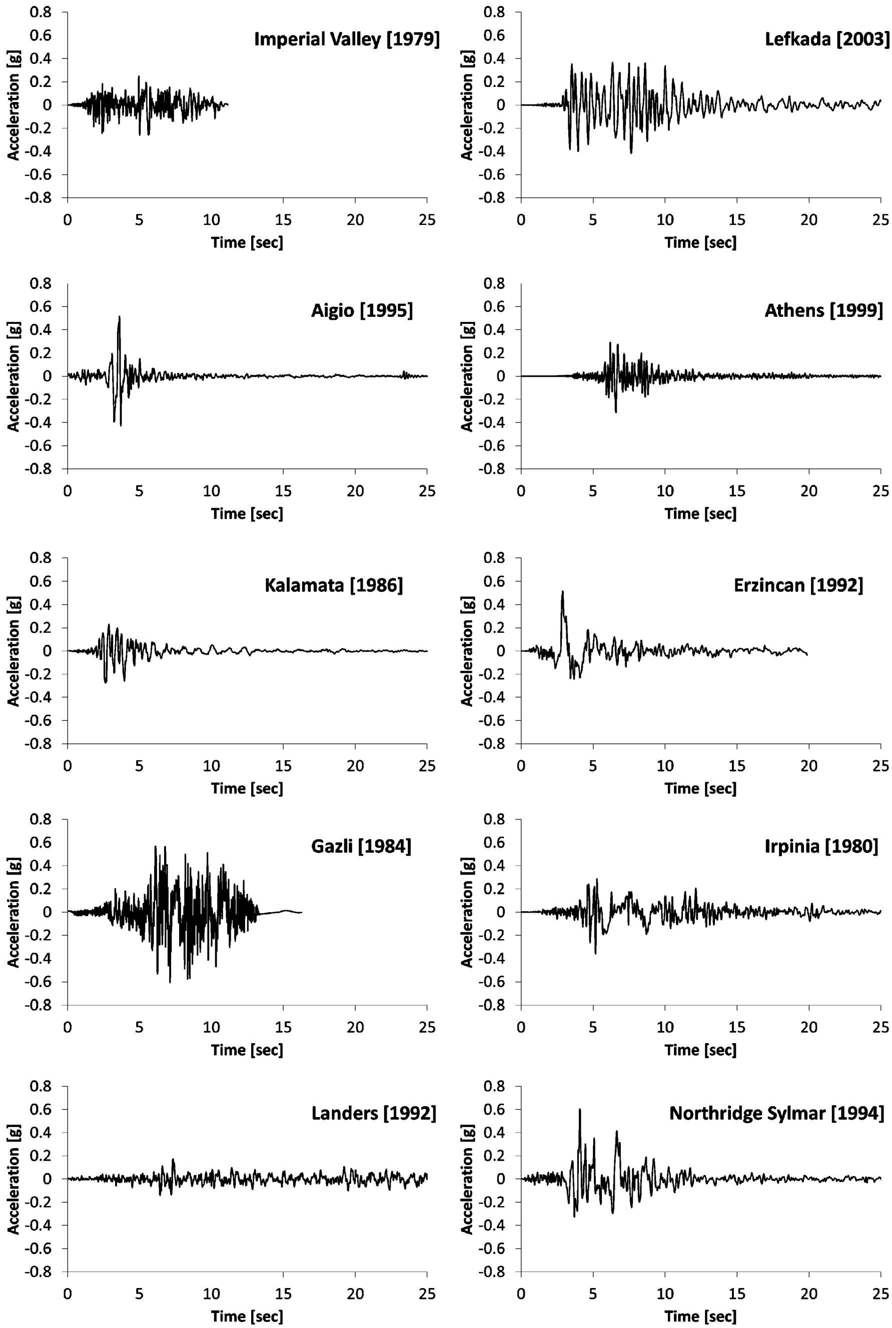
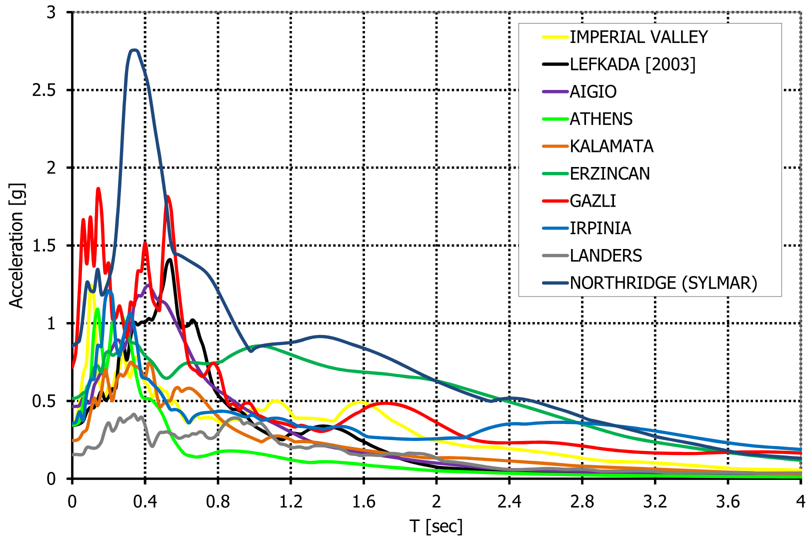
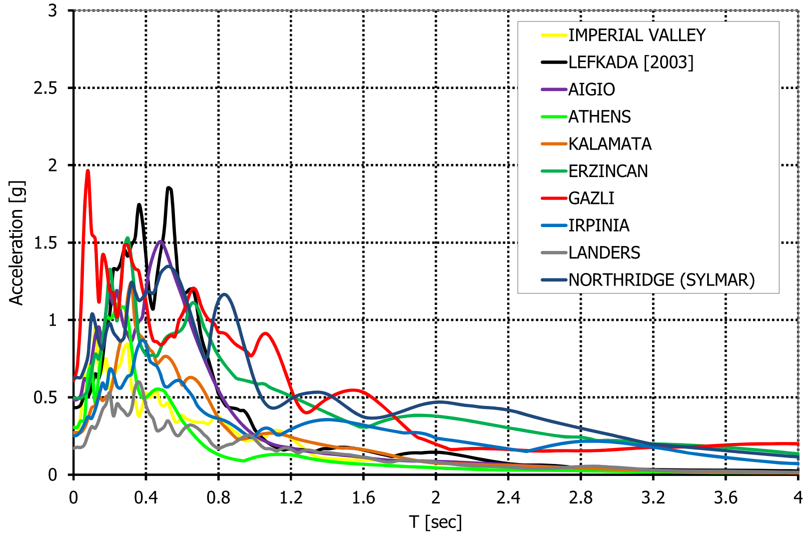


Fig. 3 Acceleration time-histories of the earthquake records applied in the transverse direction



(a)



(b)

Fig. 4 Acceleration response spectra for 5 % damping of the horizontal components of the base motions that were applied in (**a**) the longitudinal direction and (**b**) the transverse direction of the structure

The upper reinforcement bars of the architrave (No. 3 and 4) were stressed significantly less for three of the earthquake excitations (Imperial Valley, Athens and Kalamata); however, large stresses were induced to these bars for the Lefkada and

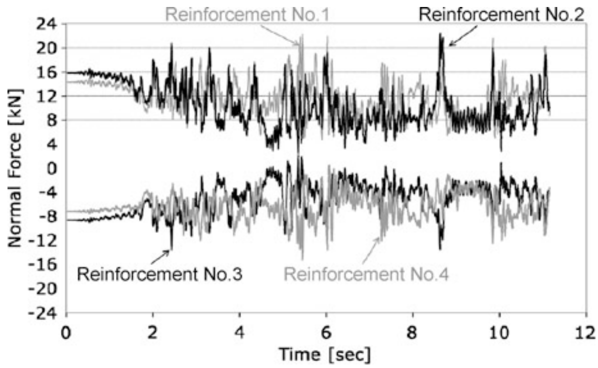


Fig. 5 Time histories of the axial forces of the 4 titanium bars of the architrave connection of the colonnade in Kos for the Imperial Valley earthquake

the Aigion earthquakes, showing that large displacements occurred at the architrave during these ground motions.

Figures 8 to 13 show the efficiency factors of the reinforcement bars used for the connection of the fragments at the drums of the columns for both case studies. It can be observed that significantly different stresses were induced to the titanium bars for each type of fragmentation, depending on the place of the intervention along the height of the column.

The worst case was observed for fragments located at the bottom drum of a column (Figs. 9 and 11); in this case almost all bars yielded for most earthquake motions.

The smallest forces were induced to the connections of the uppermost drums, e.g. the third drum of column 1 of the colonnade in Kos (Fig. 8) and the 12th drum of the column of the Parthenon Pronaos (Fig. 12), where efficiency factors less than 0.70 and 0.50 respectively were achieved in most cases.

Forces close to yield were induced to the titanium bars of connections located around the middle-height of the columns, as at the fourth drum of column 2 of the colonnade in Kos (Fig. 10) and the 6th drum of the column of Parthenon (Fig. 12).

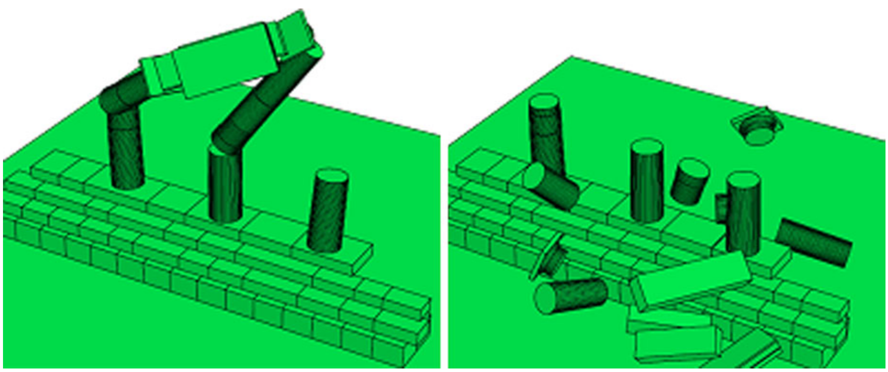


Fig. 6 Collapse mechanism of the monument in Kos for the Sylmar, Northridge, record

Fig. 7 Accomplished efficiency factors of the four titanium bars of the architrave connection of the colonnade in Kos for the five earthquake excitations that do not cause collapse of the monument

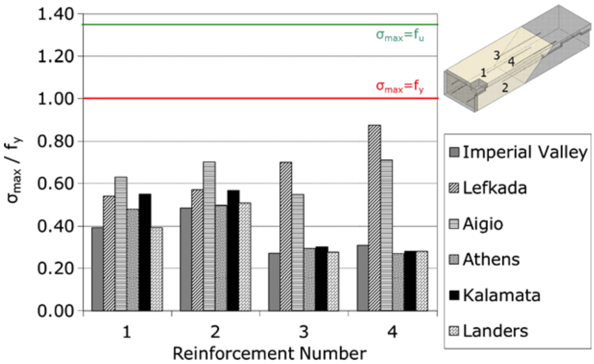


Fig. 8 Efficiency factors of the four titanium bars used for the complement of the third drum of column 1 of the colonnade in Kos for the five earthquake excitations that do not cause collapse of the monument

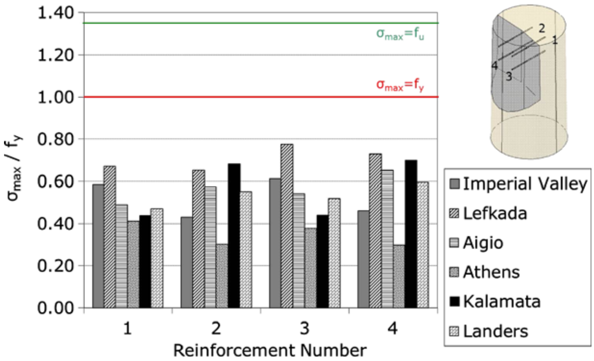
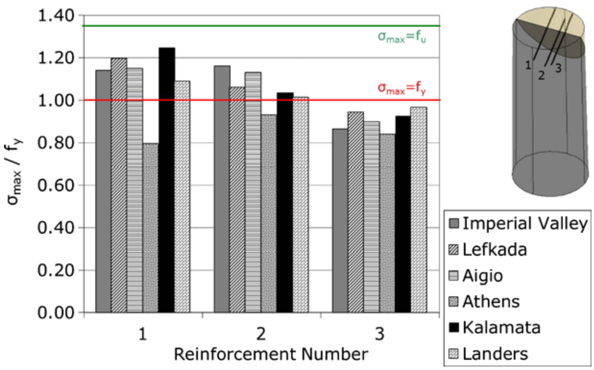


Fig. 9 Efficiency factors of the three titanium bars used for the complement of the first drum of column 2 of the colonnade in Kos for the five earthquake excitations that do not cause collapse of the monument



It should be noted that in all cases, the maximum stress was less than the ultimate limit strength of the reinforcements. In this sense, it can be said that the simplified approach for the design of the connections is, in general, adequate, although yield of the bars might occur temporarily.

It is evident from these results that both the inclination of the connection and its position along the height of the column affect significantly the forces that are induced to the reinforcement bars. The worst case concerns fragments that form a

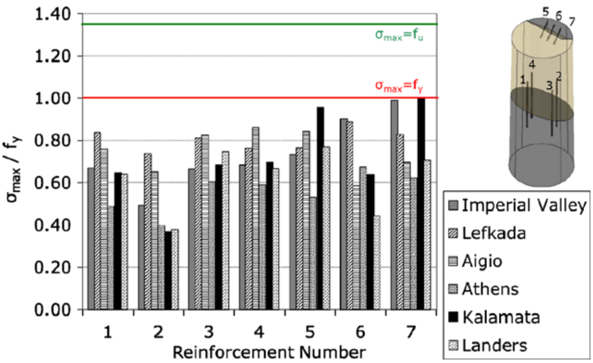


Fig. 10 Efficiency factors of the seven titanium bars used for the complements of the fourth drum of column 2 of the colonnade in Kos for the five earthquake excitations that do not cause collapse of the monument

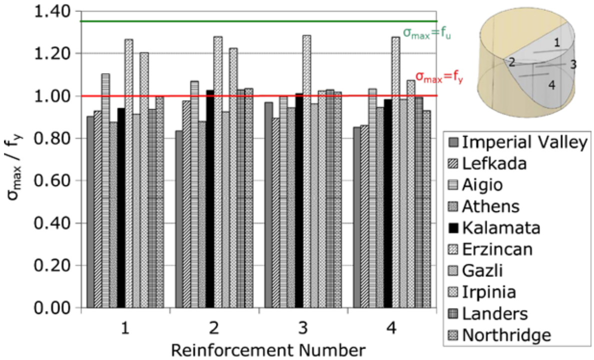


Fig. 11 Efficiency factors of the four titanium bars used for the complement of the first drum of the column of the Parthenon for the ten earthquake excitations used in the analyses

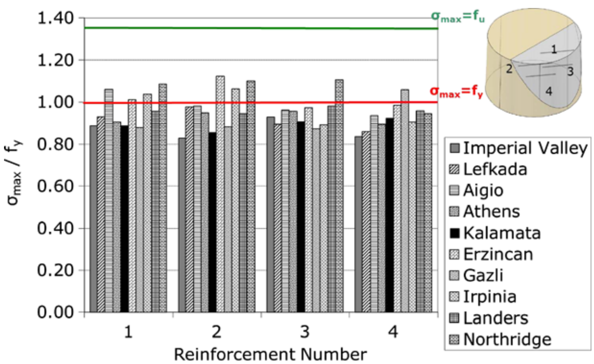


Fig. 12 Efficiency factors of the four titanium bars used for the complement of the middle (6th) drum of the column of Parthenon for the ten earthquake excitations used in the analyses

wedge and are located at the lower part of the column, where the gravity loads are larger. During rocking, large forces are developed at such connections; this was also observed in [16].

It must be noted that the obtained results concern the maximum forces that were induced to the reinforcement bars of the connections during the response of the structures examined, which, however, cannot be ascertained that they are the most adverse ones that could occur. This is because the forces that are developed at the

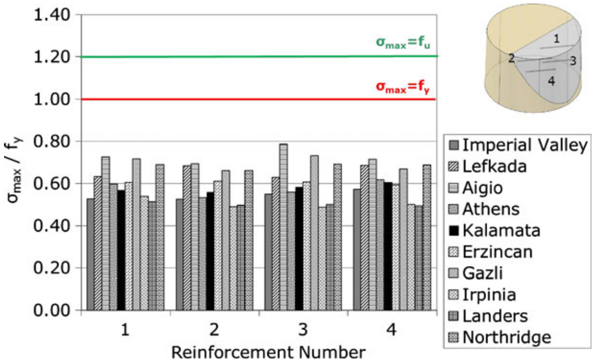


Fig. 13 Efficiency factors of the four titanium bars used for the complement of the last (12th) drum of the column of Parthenon for the ten earthquake excitations used in the analyses

connections of the complements depend on the "mode" in which the columns rock during the seismic excitation. The worst case is when the part of the column above the drum under consideration rocks around the edge corner of the fragment, which is not certain that occurred in the cases examined. However, the consistency of the obtained results for many earthquakes of different characteristics shows that the conclusions drawn are reliable for most of the cases that are expected to be encountered in practice.

6 Conclusions

The efficiency of the design of connections of fractured architraves or complements of drums of columns was evaluated from the results of dynamic analyses. The main conclusions drawn are:

- The simplified methodology that is used in practice for the dimensioning of the reinforcement of connections between new and old complements, which is based on the capacity design concept, was proved to be adequate, since the ultimate strength of the titanium bars was never reached. However, the yield stress can be temporarily exceeded. In most cases, though, the stresses induced to the reinforcement bars were considerably lower than the corresponding yield resistance.
- The position of the intervention and the shape of the fragment to be completed affect the forces that were induced to the connections. The most adverse situation was observed for fragments of column drums that formed a wedge and were located at the lower part of the column.

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