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The Restoration Study of the Connections Between the Stone Blocks in the Steps of the Temple of Apollo Epikourios

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ABSTRACT: The present work is part of the structural restoration study of the temple of Apollo Epikourios. It concerns the restoration of the connections between the stone blocks in the steps of the temple. In order to replace ancient double-T clamps, new double-T connectors made of titanium will be used. The basic criterion in designing the new connectors is that connection failure, if it takes place, should be as ductile as possible. Thus, yielding of a connector should proceed, so that damages to the connected stone pieces would be avoided. In order to attain that objective, numerical 3-D analyses were carried out for the computation of the bearing capacity of the blocks in the area of the clamps and consequently for the calculation of the maximum allowed resistance of the new connectors. For the cases of damaged stone blocks at the region of connections, a new type of connector is designed, which will be embedded and anchored into the limestone, with little damage to the mortises.

1 INTRODUCTION

The temple of Apollo Epikourios stands as one of the most remarkable monument of classical architecture (Fig. 1). It is built at Bassai, in the mid-east Peloponnesus, at 1130 m altitude a.s.l. The monument is a Doric temple and measures 16.14 X 39.84 [m] at the upper level of its foundation. The columns of the peristyle are 5.97 m high, with base diameter 1.12 m. The main building material is a white-light gray, hard but very anisotropic, limestone, taken from the local area. In its current state the temple presents many structural problems, mostly due to foundation failure which caused significant settlements and consequently fractures of the members of the steps and tilts away from the vertical position of the columns. The restoration of the monument began in 2001, focused at its north side, with basic scopes to correct the severe geometrical deformations of the structure and to strengthen its protective mechanisms.

The present work is part of the structural restoration study of the monument. It concerns the restoration of the connections between stone blocks of the temple steps. The ancient constructors put metal connectors in the majority of the stone members, with few exceptions in places where they considered them unnecessary, as between the drums of the columns. The connectors are made of iron and placed into mortises cut in the stone at invisible positions. They are surrounded by lead, for protection from corrosion. More specifically, in the first two, of the three, steps of the temple the ancient constructors placed double-T clamps to connect all the stone blocks, in both horizontal directions. Below the steps, at the upper stone layer of the foundation, clamps are placed for longitudinal connection only, close to the exterior edge of the stone blocks. The purpose of the connectors is to empower the building to maintain its cohesion and stability, in cases where significant dynamic loads break the friction ties and the interlocking between the stone blocks, deforming the structure. Connecting elements start helping the friction forces as soon as the first relative displacements of the blocks occur, giving the building some sort of pointy plasticity, due to their capacity to dissipate energy by deforming plastically.

Figure 1 : The temple of Apollo Epikourios before the beginning of its restoration.

According to the programmed intervention, new connectors made of titanium will be used in order to replace the ancient clamps and restitute the missing ones. Titanium was chosen because of its great resistance to all types of corrosion. Instead of lead, white cement mortar will be used to fill the mortises. The design of the new connectors is based on one of the main restoration principles, the preservation and the protection of the authentic parts of the monument. Thus, the basic criterion in designing the new connectors is that connection failure, if it takes place, should be as ductile as possible. Therefore, yielding of a connector should proceed, so that damages to the connected stone pieces would be avoided.

In order to study the behaviour of such connections, three dimensional numerical analyses were carried out, using the software Abaqus, which is based on the finite element method. Analyses were performed in three stages. At first, the type and magnitude of the actions at the clamps was estimated, in case a large earthquake has taken place close to the monument, which is the most probable case for loading of the clamps after the end of the restoration work. Subsequently, the reliability of the software used in the study to predict the behaviour of a connection that fails with cracking of the connected limestone blocks was examined. The examination took place by comparing data derived from experiments, where marble pieces connected with metallic dowels were loaded in shear till the marble was fractured, to the corresponding results from the numerical reproduction of the experiments. In the third stage of the analysis, in which the results of the first stage were taken under consideration, the bearing capacity of the limestone in the area of the clamp was computed, for the various dimensions of the mortises, as found in situ. Thus, for a given resistance of a limestone block in the area of the clamp, the maximum allowed resistance of the new connector can be derived and its maximum shaft thickness can be calculated.

Furthermore, the quite frequent case of locally deteriorated or damaged stone blocks at the region of connections was also considered. A new type of titanium connector was designed, which will be embedded and anchored into the limestone, causing little damage to the mortises.

2 ESTIMATION OF THE ACTIONS AT THE CLAMPS

The temple's connectors are not prestressed, thus, loading forces are being imposed on them only in case some event (settlement, earthquake etc.) causes relative displacements in the blocks. The most probable case for the connectors to be stressed, after the end of the restoration work, is that of a significant seismic event taking place near the monument. In order to estimate the type and the magnitude of the actions at the clamps in the temple steps, in such a case, a numerical analysis took place, using the software Abaqus. A portion of the north side of the monument was simulated and was excited by a seismic record of large magnitude. The software reliability in estimating the seismic response of multi-block assemblies connected only by friction was checked in a previous study, with satisfactory results (Papadopoulos 2005).

The numerical model consisted of the second from the east column of the north side, of the stone blocks of the three steps and the last level of the foundation, which are below the column, and of a base block (Fig. 2a). The model, also, included elements that represented the metal connectors of the blocks. The model's geometry definition was based on actual measurements of the temple stone members. Likewise, the positions of the elements that simulated the clamps were in correspondence to the clamps real location at the monument (Fig. 2b). The model was formatted in such a way so that stone members were simulated in the state where they will be after the restoration work; meaning as distinct (almost rigid) members, in full contact, with no relative displacement, and in vertical or horizontal positions. For simplicity purposes, the model discretization took place using 8-nodes hexahedra elements that resulted to the cross sections of the column shaft in the model to be polygonal, instead of circular with 20 flutes, as in reality.

The representation of the clamps in the model was introduced by means of reinforcement elements that correspond to springs attached between two points of the neighbouring blocks. The springs present axial and shear resistance, and elastic behaviour was assigned to them, defined by elastic stiffness with magnitude of 50.4 x 10^6 N/m, in the longitudinal direction, and of 25.2 x 10^6 N/m, in the transverse direction. The interactive behaviour of the stone blocks normal to the interfaces was defined with the use of a 'hard' contact model that allows when two surfaces are in contact, any pressure to be transmitted between them and, when the surfaces separate, it reduces the contact pressure to zero. In the tangential direction of the interfaces was used a classical friction model with friction coefficient of 0.75 (value resulted from tests, Papantonopoulos 1995). The numerical model was loaded by its own weight and it was seismically excited by prescribing at its base block the three components of motion, using the time histories of the displacement of the record of the Aigion earthquake, multiplied by a factor of 1.5. The earthquake took place the 15th of June 1995 and it was of magnitude $M_S = 6.2$. The record is dominated by a 0.5 sec period pulse and its pga, pgv and pgd are 0.54g, 48.1 cm/sec and 6.7 cm, respectively.

The numerical analysis, as it was expected, predicted both longitudinal and transverse loading for the blocks connections. The tensile and shear forces were of similar magnitude and, in the cases with the greatest values, nearly reached, or slightly surpassed, 3000 N. In Figure 3 the time histories of the connector forces that presented the greatest values at each stone layer are shown.

It should be noted that numerical analysis contains some uncertainties related to the simplifying assumptions made in the simulating process, as well to the complex parameters that influence the seismic response of rigid bodies assemblies. Moreover, the fact that a small portion of the monument was simulated, in conjunction with the estimation, derived from previous studies, that the larger seismic loads are imposed by the earthquakes at the corners of the ancient temples, further suggests that the numerical results are more reliable in quality, than in quantity terms. The objectives of the analysis, however, were firstly to ascertain the type of the actions at the clamps of the temple in case of an earthquake; and secondly, for designing purposes, to evaluate roughly the higher level of magnitude of those actions. Thus, the first objective was achieved by the type of the analysis performed, and the second was insured by the fact that for the seismic motion imposed on the numerical model, a record of magnitude greater than the usual earthquakes in the area of the temple was selected.

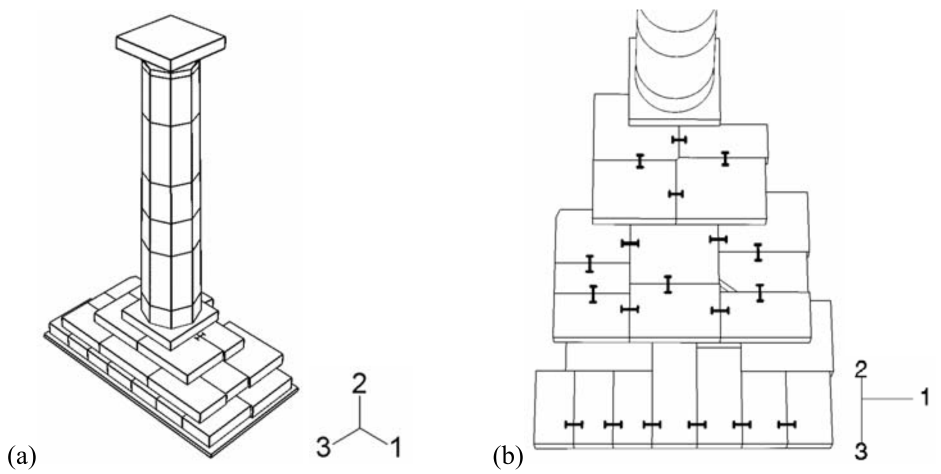


Figure 2 : Numerical model. (a) General view; and (b) location of the connecting elements (I).

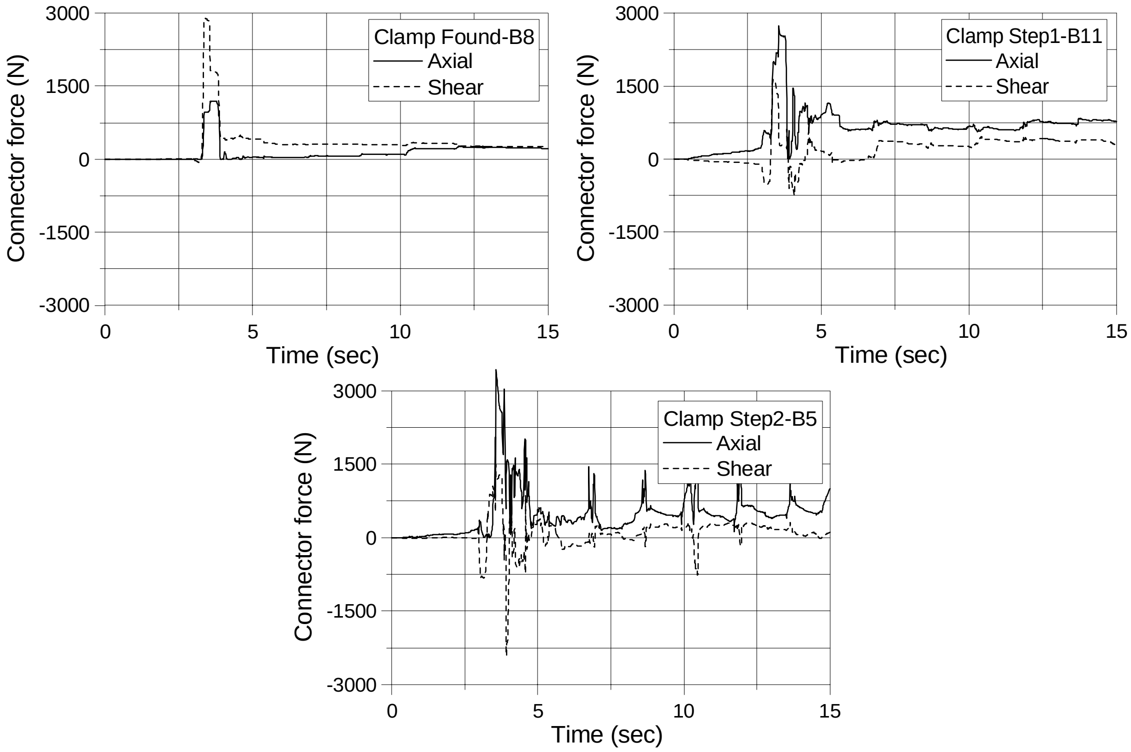


Figure 3 : The time histories of the connector forces that presented the greatest values at each stone layer

3 EXAMINATION OF THE SOFTWARE'S RELIABILITY IN PREDICTING THE CONNECTION FAILURE

Software Abaqus was also used in this study in order to estimate the bearing capacity of the stone blocks in the area of the clamps. For that purpose, before parametric computation, whether the software can reliably predict the behaviour of stone blocks connections that fail with cracking of the connected stones was examined. The examination took place by comparing data derived from five experiments in which stone connections, similar to the temple's, were loaded up to failure, to the corresponding results of the numerical reproduction of the experiments. At the experiments three marble pieces were connected with steal dowels and their connections were loaded in shear (Fig. 4a). The assumption that if the software predicts correctly the testing results then it could estimate reliably the temple's double-T connections capacity is valid, because the properties of the marble are resembling those of the limestone, and because the failure process of the dowel and the clamp stone connection are, in principal, quite similar, due to the fact that the stone fracture is dominated by tensile cracking in both cases.

In all five experiments the same dimensions were applied regarding marble pieces, 100 x 18 x 18 [cm], dowel area, 14 x 7 [cm] and dowel cover 8 cm. The dimension of the dowel width was 0.5 cm in the first three experiments and 1 cm in the last two. The load was applied increasingly until failure. The tests led to stone fracture at ultimate loading force of 205 kN, 225 kN and 250 kN, when slimmer dowels were used, and of 250 kN and 310 kN in the other case.

The simulations of the experiments were carried out in three dimensions following exactly the dimensions of their elements. For simplifying purposes the few millimetres width mortar, between the dowels and the marble, was neglected in the models. Regarding external marble elements and steal dowels, elastic material behaviour was applied, with modulus of elasticity 80 GPa and 210 GPa and Poisson's ratio 0.26 and of 0.3, respectively. The behaviour of the central marble piece was simulated using a non-linear model, suitable for applications in which the behaviour is dominated by tensile cracking. The model assumes that the compressive behaviour is always linear elastic and at failure allows removal of elements from the mesh. Tensile strength of 8 MPa and fracture energy of 128 N/m were adopted for the central marble element.

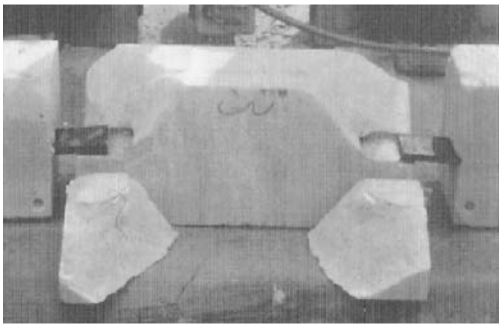
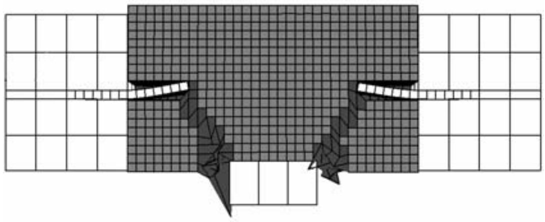
(a)  (b) 

Figure 4 : (a) Fractured marble after the experiment (Zampas 1994). (b) Deformed model at the instance of total failure. The darker grey shade indicates the cracked elements that were removed from the mesh.

Numerical results were very satisfactory as they concluded total connection failure when the load reached 230 kN, in the case of 0.5 mm dowel width, and 270 kN in the other case. The software predicted correctly also the type and shape of failure (Fig. 4b).

4 DESIGN OF THE NEW CLAMPS

4.1 The bearing capacity of the stone blocks in the area of the clamps

As mentioned previously, the design of the new temple clamps is based on the criterion that the connections, in the critical loading state, should fail with connector yielding and not with stone cracking. Thus, the maximum allowed resistance of the clamp and consequently the maximum cross section area of its shaft can be derived from the limestone bearing capacity at the region of the mortise. For that purpose, a parametric numerical analysis, that included the usual dimensional combinations of the temple connections at its steps, was carried out, in order to estimate the bearing capacity of the blocks in the area of the clamps.

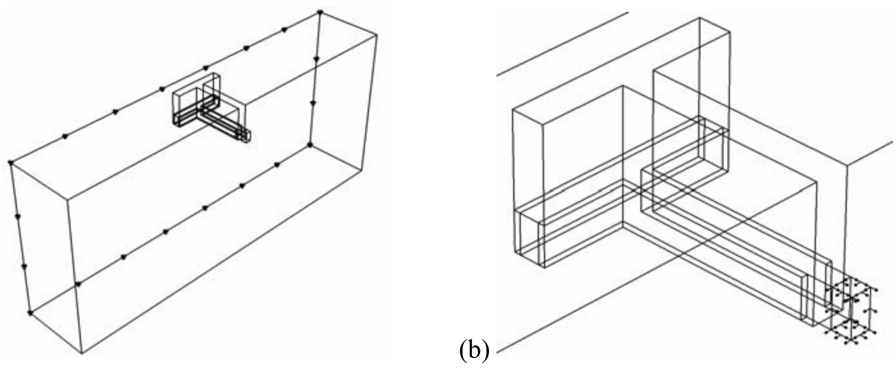
Numerical models consisted of a limestone block portion that included a mortise, half a clamp and three cement mortar pieces between the clamp and the mortise (Fig. 5). The standard dimensions in the models were: block height 25 cm, block width 60 cm (minimum clamp cover at the monument 30 cm), mortise width 13 mm, cement mortar pieces width 2.5 mm, clamp width 8 mm, and clamp height 15 mm. These values were selected as typical, based on the most frequently observed dimensions on the monument. In the models the block length was few cm longer than the clamp, the mortar was 5 mm shorter than the longitudinal section of the mortise and the clamp shaft exceeded by 13 mm of the block. The parameters their influence of which on the connection capacity was examined is the mortise depth (d), the length of the mortise longitudinal section (l), that corresponds to the half of the length of the clamp shaft (L/2), and the length of the transverse section of the mortise (b), which is equal to the length of the clamp head (B).

The limestone block was fixed at the opposite of the mortise vertical side, and the clamp was loaded in tension and in shear, simultaneously and increasingly until failure of the connection. The tension and shear load were of the same magnitude and were applied as body forces to the last 8 mm of the clamp shaft (Fig. 5b). The decision to impose combined loading upon the connector, was based on the results of the first numerical analysis. The discretization of the models took place using 8-nodes hexahedra elements. Titanium's and mortar's behaviour were simulated using an elastic model with modulus of elasticity 105 GPa and 20 GPa and Poisson's ratio 0.32 and 0.3, respectively. In order to simulate limestone behaviour brittle cracking material was used, the same used for the marble in the previous analysis successfully. The properties adopted for the limestone were based on previous relative experimental study (Papantonopoulos 1995) and are for the modulus of elasticity 80.1 GPa, for the Poisson's ratio 0.3, for the tensile strength 2 MPa and for the fracture energy 22.4 N/m.

According to the numerical results, stone failure occurs gradually with (a) shear cracks at the vertical block edge in the vicinity of the clamp, that increase as the load increases; (b) crushing of the block in the proximity of the clamp to the direction of the shear load; (c) tensile cracks at the corner of the transverse mortise section opposite to the shear loading direction, and destruction of the half mortise longitudinal section in the shear loaded side, consequently or simultaneously depending on the mortise dimensions; and (d) total destruction of the mortise and clamp extraction. For the purposes of the present study connection failure was considered the stone crushing. The loads at which it occurred are presented in Figure 7, as the stone bearing capacity, in relation to the various mortise dimensions examined (once again it is noted that the load corresponds to shear and tensile force of equal value). The appearance of the first crack in the analyses varied from 55 % to 85 % of the crushing load and in the most cases was between 65 % and 85 %. Results showed that the primary parameter that determines the load at which stone failure will occur is mortise depth. This is because the software predicted that, at the critical loading state, the stone behaviour is dominated by shear failure. More specifically, the stone bearing capacity was predicted to increase linearly with increasing mortise depth. If the greatest value result is ignored, the equation describing the relation between the stone bearing capacity and the mortise depth presents high coefficient of correlation (R = 90 %) and has the following form:

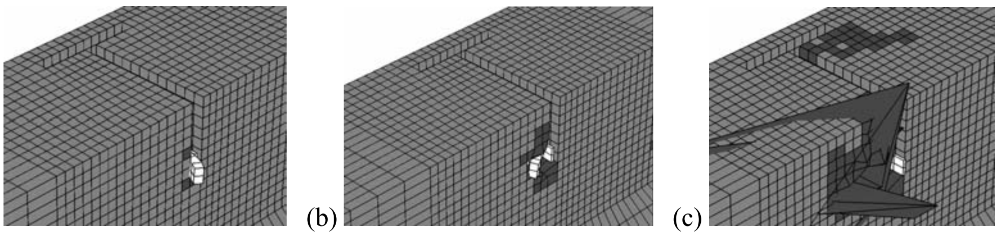
$$C = 2.8\,d + 21.2 \tag{1}$$

where C = the block bearing capacity in kN and d = the mortise depth in cm.



(a) (b)

Figure 5 : Model with B = 8 cm, L = 8 cm and D = 5 mm. (a) General view; (b) detail of the connection.



(a) (b) (c)

Figure 6 : Failure process of model with b = 10 cm, l = 12 cm and d = 7 mm: (a) shear cracking initiation; (b) crushing of the mortise vertical edge; and (c) tensile cracking and half mortise destruction.

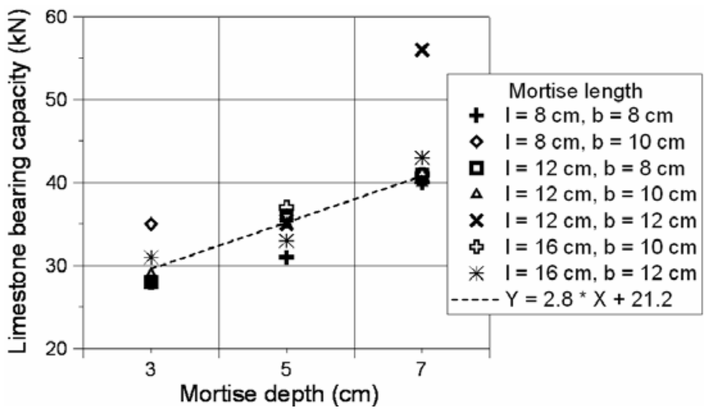


Figure 7 : The numerical results concerning the stone blocks bearing capacity in the area of the clamps.

4.2 The new titanium clamps

The new titanium clamps of the temple steps will be double-T shaped (Fig. 8, left). Their shaft and heads' length will be dictated by the correspondent mortises. Their height and width will be 13 mm and 8 mm, respectively, however in the middle shaft section their cross area will be reduced, so that their resistance does not surpass the bearing capacity of the connected stones. The design value of the clamps resistance will be calculated using the equation (1) with factors decreased by 50 %, for reasons related to the difficulty in knowing correctly the stone blocks material parameters, and in order to eliminate the possibility of shear micro-cracks appearance in the connected blocks. Consequently, for maximum titanium yield strength of 450 MPa (ASTM B265), the section area of the clamps shaft (*A*) will be derived from the formula:

$$A = 0.03\, d + 0.24 \tag{2}$$

Due to the fact that the clamps will be stressed by combined actions, it is expected that where yielding to occur this will be before the external forces reach their design value. Furthermore, titanium's minimum yield strength is 275 MPa. These are added safety factors for the preservation of the temple material. Moreover, even in the shallow mortises the new clamps will be able to develop sufficient strength to resist the seismic actions of the usual region earthquakes.

The reduction in the clamps cross area will be both horizontal and vertical. Vertical reduction will be asymmetrical, in order to impose shear loading at the low part of the mortises. In order to fill the mortises, white cement mortar will be used, leaving a void 1 cm length at the blocks interface, so as to allow clamps to deform plastically without damaging the mortises.

5 RESTORATION OF DAMAGED CONNECTIONS

There are numerous cases where the mortises of the temple connections were destroyed (when attemps were made to steal the connection metals) or have deteriorated to a great extend, due to weather conditions. It is obvious that in these cases, double-T clamps cannot sufficiently interlock with the stone blocks to insure connection. For those cases a new type of connector is designed. The new type connectors will be similar to the new double-T shaped clamps, with an addition of two vertical legs in the junctions of the shaft with the heads (Fig. 8 right). The vertical legs will be formed in such a way so that when they will be embedded with cement paste in holes at the mortises, they will be anchored. Consequently, the connection of the stone blocks will be insured with limited, non-visible damage to the mortises. The length of these vertical legs will depend to the extend of the damage of the mortises and will vary from 0.6 times the half length of the clamp shaft, in cases where mortises present little damage, to 0.9 the half length of the clamp shaft in cases where mortises present total damage. The damaged mortises will be reformed using cement mortar with colour resemblance to the blocks and sufficient strength, and the filling of the mortises will take place with the relieving void (Fig. 9).

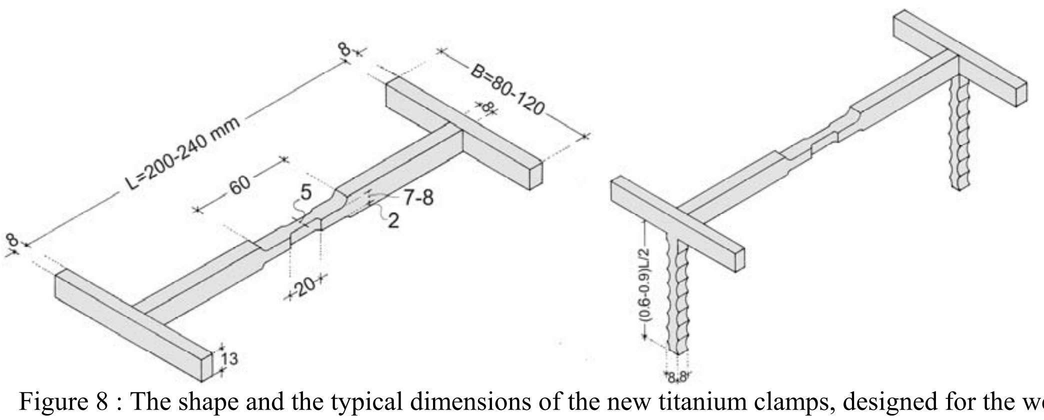


Figure 8 : The shape and the typical dimensions of the new titanium clamps, designed for the well preserved mortises (left) and for the damaged or severely deteriorated mortises (right).

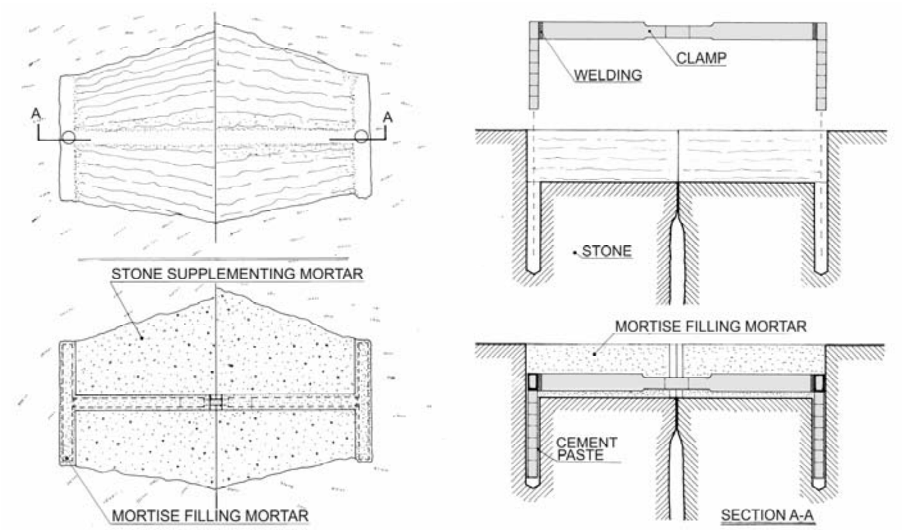


Figure 9 : Restoration of connections with damaged or severely deteriorated mortises.

6 CONCLUSIONS

The basic objective of the present work was to design the new titanium clamps of the connections between the stone blocks in the steps of Apollo Epikourios temple. The new clamps have to strengthen the monument's seismic capacity, without damaging its authentic parts. In order to insure that, clamps must present resistance higher than the seismic loads anticipated, and, more importantly, lesser resistance than the bearing capacity of the limestone blocks at the regions of the connections. In order to design such clamps, numerical analyses were carried out so as to estimate the seismic actions at the clamps and to compute the blocks bearing capacity.

The complexity of the seismic response of ancient monuments, the uncertainties concerning the strength of the temple blocks and the simplifying assumptions made in the analyses, question the accuracy of the study results. However, taking into account the software reliability when predicting the seismic response of rigid block assemblies (Papadopoulos 2005), the satisfactory outcomes of the examination of the software's capacity in predicting stone connection failure and the fact that the shape of the new clamps favours connector plastic deformation before stone cracking, it is assumed that the goals of the present study will be accomplished.

ACKNOWLEDGMENTS

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