Computational modelling of the mechanical behaviour of the Pentelic Marble -Steel clamp system on the structures of the Athens Acropolis

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Abstract **– Computational modelling is employed to investigate the mechanical behaviour and failure scenarios of the Marble block - Steel clamp ancient masonry system utilized on the Athens Acropolis monuments, under static loading and modal analysis. The input data for the model are acquired by laboratory testing results such as tensile strength measurements and metallography, as well as bibliographic sources from various scientific fields (i.e. materials properties, archaeometry, restoration, structural engineering and geology). The effects of corrosion to the mechanical behaviour of the clamps are examined for two types of steel (E = 50 and E= 200 GPa) and the mechanical behaviour of the clamp - marble block system is examined for three realistic scenarios: (a) a well preserved ancient clamp, embedded in cast lead metal, (b) a well preserved early 20th century restoration clamp, embedded in Portland cement mortar and (c) a heavily corroded clamp surrounded by corrosion products. The aim is to build up a methodology that will take into account different states of preservation of the original and/or the restoration materials. This methodology could evolve further and be used as input for scaling up to structural engineering modelling.**

I. INTRODUCTION

Steel clamps and dowels inserted in the marble blocks of the Athens Acropolis monuments have maintained the structural integrity of the walls and other architectural parts from 5th century BC until 1687, when the bombardment of the Parthenon resulted to the partial collapse of the building structures and exposure of the metal elements to the corrosive environment. During restoration interventions in the beginning of the 20th century many of the original metal pieces were replaced by modern steel (sometimes as reinforcement of concrete). Both original and restoration steel were severely corroded by the atmospheric environment that prevailed during the1960s as a result of the industrialization of Athens and the extensive use of high sulphur content fuels, which has also caused sulphation of the marble surface[1,2,3]. The Ministry of Culture decided to remove most of these metals and replace them by titanium alloy metal clamps and reinforcements [3]. Steel clamps, ancient and modern, are still being removed from the walls of the monuments as the restoration program of the Acropolis monuments proceeds.

For the scope of this research three steel clamps, two T-shaped (S200, S214) and one Π-shaped (S245), provided to the authors by YSMA (Acropolis Restoration Service) [4], were submitted to a series of mechanical tests, microscopic evaluation, 3D scanning and electrochemical corrosion testing. The results were compared to literary sources. This short paper includes only a part of the obtained data which are necessary for the presentation of the computational modeling of the mechanical behavior.
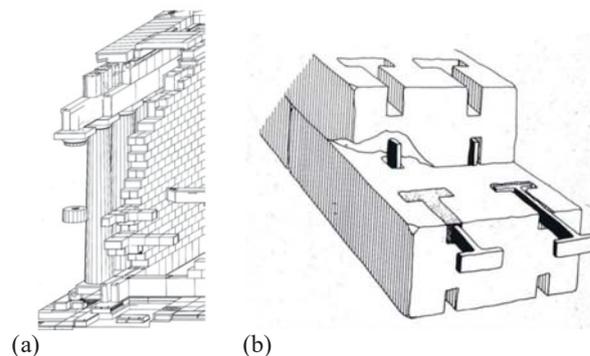

(a)   (b)

Fig. 1.(a) A schematic presentation of a wall of the Athens Parthenon (b) A schematic presentation of the application of -embedded in cast lead metal- steel double T's and dowels to connect the marble blocks. (source: A. Orlandos)

II. EXPERIMENTAL

A. Laboratory testing

Elemental chemical analyses of the steel clamps were conducted by an ARL3460 automatic Optical Emission Spectrometer (OES) at Halyvourgiki Inc. laboratories. Tensile stress tests were performed by a Roell Amsler System MFL UPN 1000 apparatus at Halyvourgiki Inc. laboratories on specimens cut out of the three clamps (S.200, S.214 and S.245). The assessment of the experimental data for the calculation of the mechanical properties of the clamp specimens was performed with respect to the EN 10080 (2005) Standard, taking into consideration the actual geometric characteristics of the specimens. Fracture surfaces were examined by means of Scanning Electron Microscopy, using a FEI 200 SEM equipped with a tungsten filament and an Everhart-Thornley Detector.Micro-Hardness Tests were performed by an Instron Wolpert GmbH V-testor 4021.

B. Computational analysis

All of the Finite Element Analysis simulations were performed with the multi-purpose finite element software ANSYS (Workbench 15.0). ANSYS enables to design complex components to depict the geometry of a system (CADs). In addition, it discretizes the structure to finite elements, estimating the mechanical behaviour of the system. It can be utilized to estimate the deformation of the structure under static loading and modal analysis. ANSYS (Workbench 15.0) was employed for the modelling of the mechanical behaviour of the clamp representative of those that were used in the Acropolis of Athens monuments restoration between 1894 and 1934. The ANSYS Design Modeler was used to design the structure geometries. In our case-study, ANSYS was used for static and modal analysis. The mechanical properties which are required for the model are: Density, Young's modulus of elasticity, Poisson's ratio, Tensile Yield Strength, Ultimate Tensile Strength as derived from the stress-strain curves. In addition, for both static and modal analysis, the utilized boundary conditions will be presented in the next section. Each simulation took approximately 8 hours of computer time.

III. RESULTS AND DISCUSSION

A. Chemical composition & Mechanical Properties

The OES results indicate that all three samples have a carbon concentration between 0.008 and 0.085%. The S.214 clamp has the highest C content (0.085%). According to the thermodynamic data on steels (Metastable Fe-C diagram [5]) S.214 is identified as a hypoeutectoid plain carbon steel, because its C content is between 0.025 and 0.8%. Clamps S.200 and S.245 with a C content below 0.025%, although typically low alloy steels, should be categorized as irons due to their ferrite

Table 1. Measured chemical composition and mechanical properties of steel clamps

	Clamps S.200, S.214 &S.245	Ancient low carbon T-clamps studied by G. Varoufakis [6]
% Carbon	0.008 - 0.085	0.002 - 0.12
Hardness Vickers (HV)	30.77 - 40.43	max. 107
Tensile strength (MPa)	322 - 410	max. 380
% Strain	11.4 - 18.9	-

matrix [10]. The results are in accordance with ancient low carbon T-clamps analysed by G.Varoufakis [6].

The examined reinforcement materials exhibit very low hardness and their stress-strain curve exhibits the typical patterns of ductile fracture. The measured ranges of hardness, tensile strength and % strain are given in Table 1. These values approximate relevant measurements by G. Varoufakis [6] on ancient T-clamps. The reduced hardness is attributed to the low C and Si concentrations.

Upon fracture the clamps are more or less prone to a ductile fracture mechanism. Among the three examined steel clamps, S.214 was selected due to its extensive microstructure heterogeneity and its unique resemblance with the ancient materials characteristics [7]. As can be observed on a polished cross-section (Fig.2) the manufacturing process resulted in a composite material. It is evident that hypoeutectoid steel and a low carbon iron alloy sheets were cladded and folded. The metallographic observations after chemical etching reveal the various microstructure characteristics of the distinct zones A, B and C marked on Figure 2. The recrystallised grain of all zones testify to the absence of intense cold working processes during the manufacture process (Fig.3). The grain orientation of the thin superficial layer above zone A -not presented in the two OM photographs- indicates a final mild work hardening process of the surface. The fractography of S.214 clamp provides a variety of ductile fracture patterns, which is characterized by the dimple structure (Fig. 4). Some areas exhibit a more brittle fracture type. A more detailed presentation of the fracture characteristics should be discussed in a specific study and will not be addressed in this work.
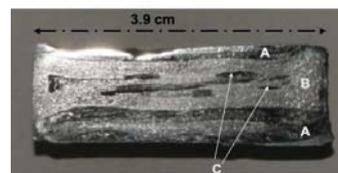

Fig. 2. *Macrophotographic documentation of clamp S.214 cross-section. Marked areas A and C correspond to external and internal hypoeutectoidsteel zone, while B correponds to low carbon iron zone.*
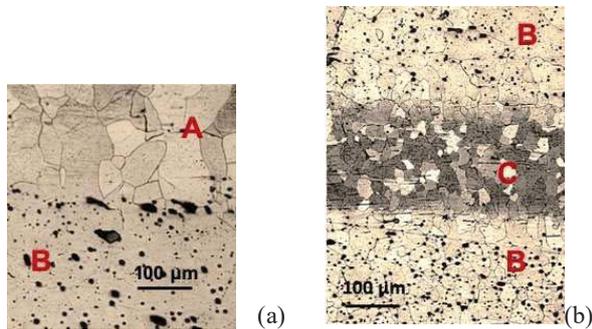
Fig. 3. *Optical microscope photograph (x100) of S.214 clamp cross-section, chemically etched with 2% Nital reagent. (a) Interface of the hypoeutectoid steel zone A (top) and the low carbon iron alloy zone B (bottom), inside which MnS inclusions are visible. (b) Hypoeutectoid steel zone C interposed between two low carbon iron alloy B zones.*
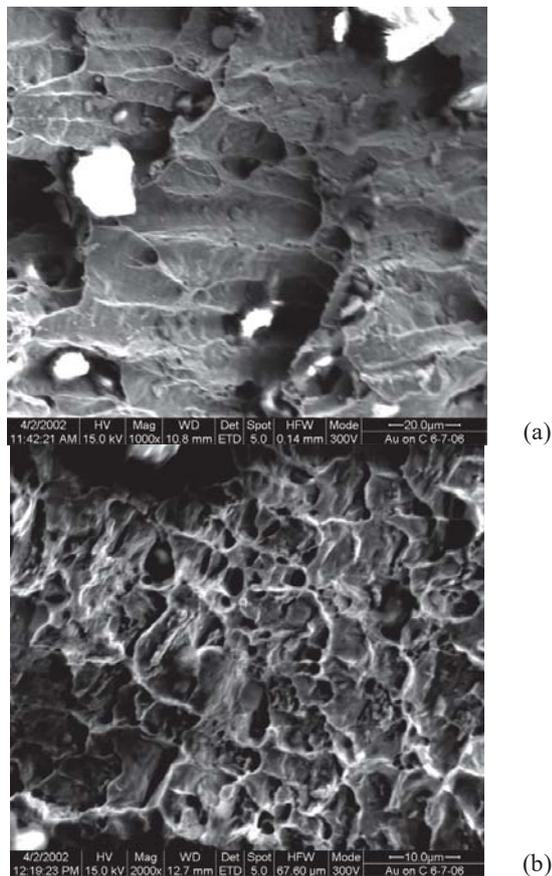

Fig. 4. *Secondary Electron micrographs of clamp S.214 fracturesurfaces (a) x1000 and (b) x2000, acquired by SEM. Characteristic ductile fracture dimples cover most of the fracturesurface.*

B. Computational modelling

Computational modelling has been performed using as input parameters the experimental values obtained for the S.214 clamp and bibliographic data for all other materials (Tables 2,3).

The first group of simulations (Simulation 1) aims to investigate the effect of corrosion to the mechanical properties of the clamp. Simulation 1 examines the steel clamps per se, under different degrees of corrosion-represented by different thicknesses of the metal core-and for the case of two different values for the modulus of elasticity.

The second group of simulations, constitutes of three simplified models of the system of a clamp restrained in a tight marble nesting (Fig.5). These models aim to simulate some realistic situations such as: (a) non-corroded clamp (7.6 cm thickness) embedded in cast lead metal, tightly fitted in the marble nesting, representing a well preserved ancient clamp (Simulation 2), (b) a non-corroded clamp (7.6 cm thickness) embedded in concrete, tightly fitted in the marble nesting, representing a well preserved early 20th century restoration clamp (Simulation 3) and (c) a heavily corroded clamp (3.0 cm thickness), covered by a first layer of compact corrosion products and a second layer of loose corrosion products and voids (Simulation 4). This last scenario is more challenging, since the determination of the actual mechanical properties of corroded steel reinforcement is yet an open challenge in the fields of corrosion science and structural engineering [8,9]. Table 4 summarises the four different simulations that were performed.

In the case of static loading, the stresses that develop on the metal joints during earthquakes depend on the position of the clamp or dowel in the walls of the structure. Thus, for a North-South direction earthquake the walls that are parallel to this direction will be affected by tensile stresses, while the perpendicular ones will receive shearing stresses. When a body is stressed by tensile and shearing stresses, all these types of stresses can be converted to what is called equivalent Von Mises stresses, which are considered as tensile stresses.

Table 2. Model input data for steel clamp and lead

	Steel Clamp	Lead
Density d (kg/m^3)	7850	11340
Young's modulus E (GPa)	50 (200)	14
Poisson ratio v	0.303	0.42
Tensile Yield Strength σ_y (MPa)	250	18
Ultimate Tensile Strength σ_y (MPa)	330	27

Table 3. Model input data for lead metal, concrete and corrosion products

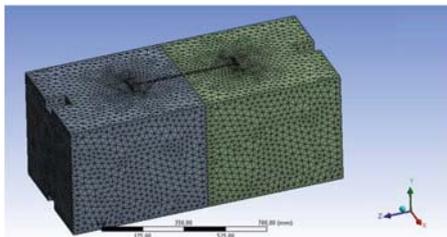|		Pentelic Marble	Concrete	Corrosion products
Density (kg/m³)	d	2710	2400	8000
Young's modulus (GPa)	E	14.7	47.8	91
Poisson ratio v		0.26	0.328	0.24
Ultimate Compressive Strength (MPa)	σ_y	113.8	37.5	3.5
Ultimate Tensile Strength (MPa)	σ_y	5-15	5	3.5

Fig. 5. *Marble block mesh grid for the finite elements analysis.*

In the case of modal analysis, the object inertia will respond, depending on the geometry, the mass distribution, the stiffness distribution and the boundary conditions of the supports. While there is an infinite number of natural frequencies that actuate the body, in practice there are only few that will affect the object's response (the transient state of the displacement). These produce a superposition of characteristic modes i.e. the characteristic movements that the mass of the object will perform, which are called 'mode shapes or eigenvectors'. Modelling results for the unrestrained clamp (Simulation 1) indicate that, while a non-corroded clamp would withstand a perpendicular (i.e. when the marble blocks oscillate but remain in place - bending) load of 8kN, a heavily corroded one would fail under the same scenario. In the case of the marble blocks being able to move away from each other (in case of collapse - stretching), even the most rigid of the examined clamps would not prevent the catastrophe. Modal analysis of unrestrained clamps shows the dependency of the natural frequencies corresponding to the first mode (i.e. the lowest natural frequency) on the clamp thickness and modulus of elasticity values (Table 5).

Table 4. Summary of the simulations

First Group

Simulation 1   Free moving clamp

Modal analysis for the determination of the modal frequencies of the clamp
Run for several thicknesses (7.6 to 3.0 cm) in order to represent metal loss induced by corrosion of the clamp
Run for a typical value of E=200 GPa and for the measured value of E=50 GPa

Second group   Clamp - marble system

Stretching (parallel) and bending (perpendicular) stressing induced by an acceleration of 11 m/s2 enforced for a period of 1 s
Run for thickness of 7.6 or 3.0 cm and for modulus of elasticity E=50 GPa
Modal analysis for the determination of the modal frequencies of the system

Simulation 2   "Preserved ancient clamp"
Well preserved clamp (7.6 cm) embedded in cast lead metal in the marble nesting

Simulation 3   "Preserved early 20th century restoration clamp"
Well preserved clamp (7.6 cm) embedded in Portland cement mortar in the marble nesting

Simulation 4   "Heavily corroded clamp"

Heavily corroded clamp (3.0 cm) surrounded by corrosion products in the marble nesting

Earthquake frequencies usually do not exceed the 20 Hz limit of human hearing, though values as high as 25 Hz can exist. The 1999 Athens M5.9 earthquake frequencies were in the range of 0.01 to 2 Hz [10]. Comparing these values with the calculated resonant frequencies of the clamps, we observe that if the metal has a typical 200 GPa modulus of elasticity, the geometry of the clamp is such, that only after its thickness has been reduced to less than half, the λ_1 falls in the frequency range of local earthquakes. On the other hand, for a modulus of elasticity of 50 GPa (the value that has been measured for S.214 clamp), even small reduction of the original thickness leads to natural frequencies in the earthquake range.
In the case of the restrained clamps (Second group of simulations) all the static loading models lead to small values of developed stresses. In the case of stretching, the stresses, though negligible for inflicting damage to the metal clamp, are large enough to initiate failure in weak

Table 5. Natural frequency corresponding to the first normal mode (λ_1) as a function of decreasing double-T arm thickness, calculated for two values of elasticity

Thickness (mm)	λ_1 (Hz) for E= 50 GPa	λ_1 (Hz) for E =200 GPa
7.6	33.116	66.232
6.45	28.18	56.362
5.3	23.208	46.416
4.15	18.202	36.405
3.0	13.162	26.321

paths that transverse the bulk of the non uniform natural stone. In the case of bending (Fig. 6), both displacement and stress are negligible (2 μm and 0.17 MPa respectively), but it is important to notice that the distribution of stresses, mainly near the dowels, corresponds to the actual damage that the monument suffered as a result of the 1687 explosion [11]. Modal analysis results indicate that the system of a clamp restrained in the marble nesting would not reach natural frequencies in the case of an earthquake, as for the lowest resonant frequency λ_1 equals 331.25 Hz.

In the case of Simulation 2 ("preserved ancient clamp") one can observe that the introduction of very soft and ductile material such as lead metal between the steel clamp and the marble, not only protects the steel from corrosion, but reduces the stresses that are exerted both on the clamp and the marble blocks. The maximum Von Mises stress values in this case are 2.34 and 0.09 MPa for the stretching and the bending scenarios respectively (Fig. 7a, 7b).

In the case of simulation 3 ("early 20th century restoration clamp"), in which the clamp is embedded in concrete, the maximum Von Mises stress values are 2.50 and 0.80 MPa for the stretching and the bending scenarios respectively. It is worth noticing that, while the substitution of lead metal by concrete has a very small effect on the stresses that develop during stretching, the stresses that develop during bending are increased nearly by an order of magnitude. Thus becomes evident the importance of the material that fills the space between the clamp and the marble.
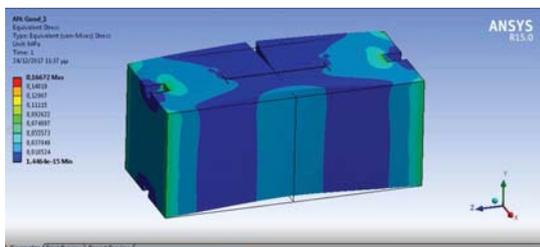
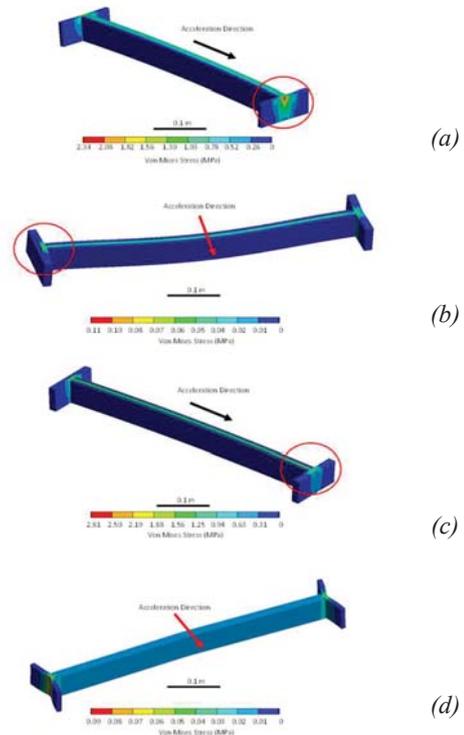Fig. 6. *Marble block - steel clamp system. Equivalent (von-Mises) Stresses: bending.*

Fig. 7. *Marble block - steel clamp system. Equivalent (von-Mises) Stresses: non corroded clamp embedded in lead metal (simulation 2), stretching (a) and bending (b) - heavily corroded clamp surrounded by corrosion products (simulation 4), stretching (c) and bending (d)*

In the case where the lead has been removed and the void has been filled by corrosion products (Simulation 4), the maximum Von Mises stress values are 2.81 and 0.11MPa for the stretching and the bending scenarios respectively (Fig. 7c, 7d).

As far as the clamp nestlings are concerned, all three of the simulations 2 to 4, indicate that the maximum stresses that are exercised near the clamps are around 0.03 to 0.04 MPa (Fig. 8)

Summarizing the results of the computer simulations, one should note that the models are based on two half marble blocks, which undergo a stimulus produced by a typical earthquake acceleration at ground level. Thus, the acceleration magnitude and consecutively the forces, which the system under investigation withstand, would be much greater if the marble blocks - clamp system was part of an oscillating masonry structure. Under this consideration and with the exception of the models for the free moving clamp, the results should be viewed only in relation to each other. What is most interesting are the changes induced by the different materials that can be present in the space between the marble and the clamp.
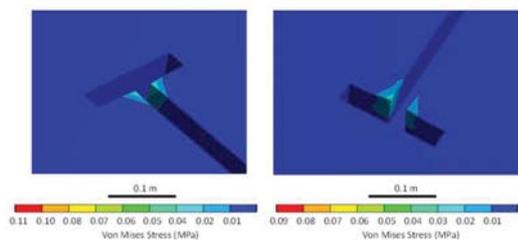
Fig. 8. *Marble block - steel clamp system. Detail of marble near clamp nesting during bending. Equivalent (von-Mises) Stresses: non corroded clamp embedded in lead metal (left) and heavily corroded clamp surrounded by corrosion products (right)*

IV.   CONCLUSIONS

The examination of the three early 20th century period double-T clamps confirms that even though different types of Fe alloys (Carbon concentration range: 0.008-0.085%) and metallurgical processing has been used, all joints exhibit low values of Micro-hardness, Tensile strength and Young's modulus of elasticity. During fracture are mostly prone to a ductile fracture mechanism. Clamp S.214 in particular, is a composite material produced by cladding and folding of a hypoeutectoid steel and a low carbon iron alloy, which has very similar metallurgical characteristics compared to the original ancient clamps.

The lowest resonant frequencies of corroded steel clamps that have lost significant part of cross-sectional thickness and are free to move, are within the range of earthquake frequencies. The original marble-clamp system and any restoration system where the clamp is restrained in a nesting, have considerably higher resonant frequencies.

While clamps cannot support the marble blocks in case these become free to move i.e. in case of collapse, when the clamps remain constrained, they seem to be able to withstand usual earthquake loads, although this question cannot be answered with certainty unless a scale up to a masonry structure simulation has been performed. Nevertheless the simulations indicate that, during earthquakes, local damage can occur on weak points of the marbles.

Even though the magnitude of generated stresses in the bending scenario are very small, the distribution of the stresses, which become maximum near the dowels, is in accordance to the damage induced on the lower parts of the Parthenon due to the 1687 explosion and to the models published by E. Toumbakari.

The presence of a highly ductile material, such as cast lead metal between the marble and the steel clamp, not only protects the ferrous joint from the corrosive environment, but also reduces the stresses that develop when the marble blocks are forced to move perpendicular to the axis of the clamp.

The next step of this work would be to use 3D scanning as input for complex geometry modern restoration titanium clamps and the final aim is to scale up from the study of single elements to actual reinforced marble masonry structures.

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