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A COMBINED EXPERIMENTAL AND NUMERICAL STUDY OF THE PULL-OUT MECHANISM OF THREADED TITANIUM BARS EMBEDDED IN MARBLE BLOCKS

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Abstract. *The present study describes the first stage of an ongoing research project aiming to investigate the failure mechanisms activated when reinforcing bars are pulled-out from the body of the reinforced element. Attention is given to the progressive failure of the interfaces between the constituent elements of the marble-cement paste-titanium (MCT) complex, which appears in case marble structural members of classic stone monuments are restored according to the pioneering technique used on the Acropolis of Athens worksite. Experience from already implemented projects indicates that, when restored structural members are subjected to tension or bending, the failure of these interfaces leads to debonding and finally to catastrophic pull-out of the reinforcing bar from the body of the marble volume.*

In this direction, a series of pull-out experiments were implemented, with specimens made of Dionysos marble, in the form of prisms of various dimensions with threaded titanium bars inserted into predrilled holes which were then filled with suitable cement paste. The results obtained from these experiments, by employing both conventional and innovative sensing techniques, were used for the calibration of a Finite Element model, which will be used for the thorough investigation of the parameters affecting the overall response of the restored element.

The commercial package ABAQUS was used for the implementation of the numerical analysis. The surface contact features of the package were properly exploited in the direction of comparatively exploring and evaluating of possible modeling approaches for simulating the actual interfaces of the marble-cement-titanium complex. A reliable performance law, allowing for the incorporation of damage initiation and evolution criteria, was determined permitting satisfactory modeling of the pull-out behavior at the interface between marble and cement paste. Critical parameters, material properties and modeling choices that have a significant impact on the final outcome were considered. The numerical model finally designed approaches in a very satisfactory manner the experimentally obtained load-displacement curve, providing an easy-to-use, flexible and reliable tool for further study of the pull-out phenomenon.

1 INTRODUCTION

The pioneering technique that is nowadays adopted for the restoration of fractured structural members of classic marble monuments of Greek architecture is based on the insertion of threaded titanium bars into pre-drilled holes, while filling the intermediate gap with a suitable cementitious paste (Fig. 1) [1]. The number and the diameter of the bars are chosen in such a way that the restored epistyle sustains its self-weight and the weight of the structural elements that are planned to be superimposed on the structure in the future. Furthermore, attention is paid for the extent of interventions to the authentic marble to be the minimum possible. The basic principle that governs this kind of restorations is the reversibility of the interventions. This means that if needed, the monument can be restored to its condition prior to the intervention.

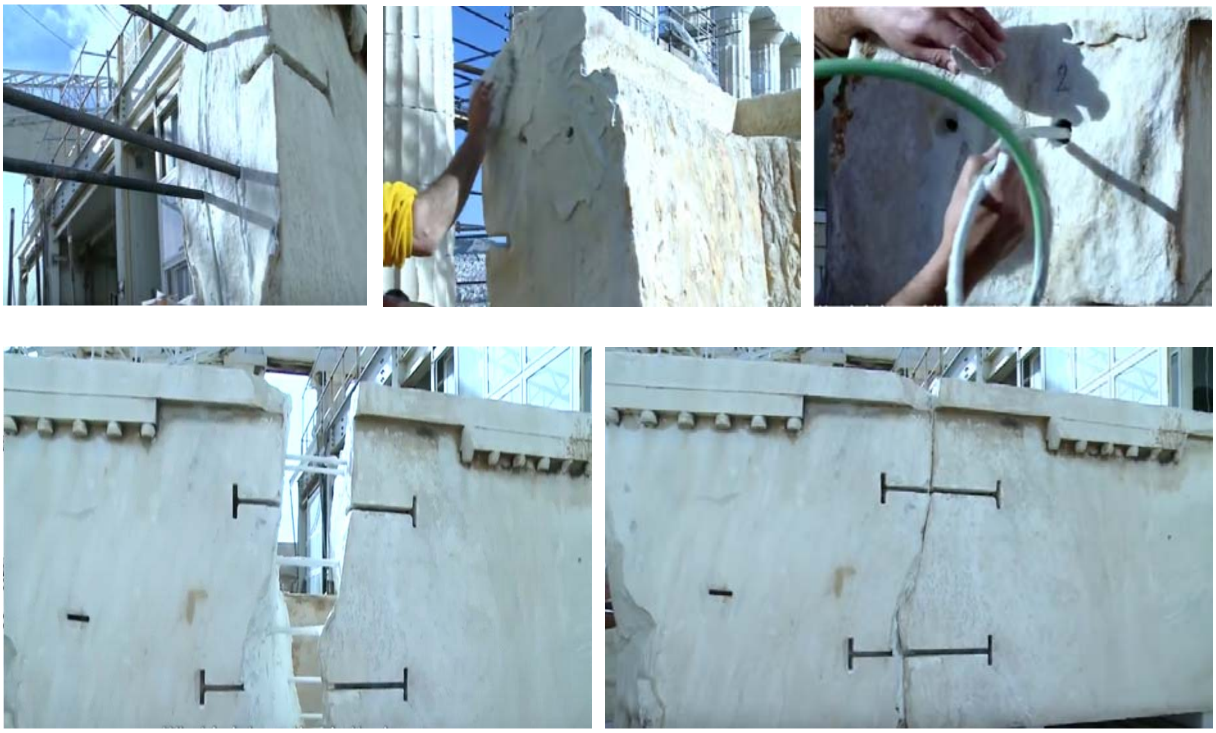

Figure 1: The main steps for the restoration of a marble epistyle [2].

Experience gathered by the scientists working for the restoration project of the Acropolis monuments has shown that the integrity of the structure after restoration strongly depends on quite a few details of the aforementioned technique. Several experimental and numerical studies have been conducted, investigating the parameters that influence the mechanical response of the specific joint [3]. It has been definitely proven that the weakest link of the three materials (MCT) chain lies within the layer of the cementitious material [3, 4]. The failure mode most commonly observed, is the relative slip of the bar-mortar block with respect to the marble volume (without fracture of neither the marble nor the bar) which is known as pull-out.

This work focuses on the development of a reliable numerical model that, hopefully, could effectively describe the behavior of a thin layer between the cement paste and the marble body while being effective concerning the computational time. Critical parameters influencing the effectiveness of the model in terms of time requirement are considered to be the model's meshing, the analysis of time-increment and the choice regarding two or three-dimensional modeling. The models developed are calibrated taking advantage of the data for the load-displacement curve of a series of pull-out experiments which were implemented at the Laboratory of Testing and Materials of the National Technical University of Athens.

2 EXPERIMENTAL PROCEDURE

2.1 Specimens

The specimens tested were orthogonal prisms cut from Dionysos marble blocks. Their dimensions were equal to 10x10x15 cm^3. A central through hole, of diameter equal to d_{hole}=14 mm, was drilled normally to the upper face of the prisms. The hole was then filled with liquid cementitious material and a threaded titanium bar, of outer diameter equal to d_{bar}=11.0 mm, was driven in the hole and kept normal to the upper face of the cube until setting of the cement paste. All specimens have the same dimensions, anchoring length (7.5 cm) and thread's geometry and were cured for 28 days (Fig. 2). Attention was paid for the prisms to be cut normally to the material layers of the blocks in order to reduce scattering due to marble's anisotropy.

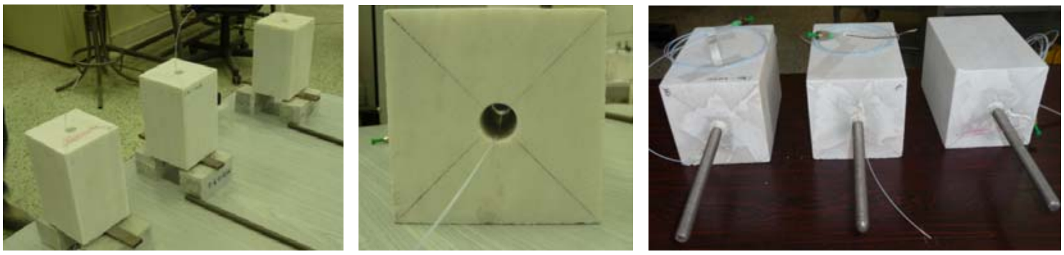

Figure 2: Preparation of the specimens.

2.2 Experimental procedure

For the experimental procedure, a stiff servo-hydraulic INSTRON loading frame of capacity 250 kN (Model 1126) was used. All tests were carried out under quasi-static displacement-control mode at a rate equal to 0.2 mm/min, with the titanium bar gripped by the frame's upper jaw. The marble cube was constrained by a rigid metallic plate with a hole of diameter equal to 50 mm in its center. The plate was supported by four stiff threaded bars (Fig. 3 (a), (b)). For the direct measurement of the axial strain developed along the titanium bar an Instron-Dynamic Extensometer of gauge length equal to 12.5mm was used (Fig. 3 (c)).

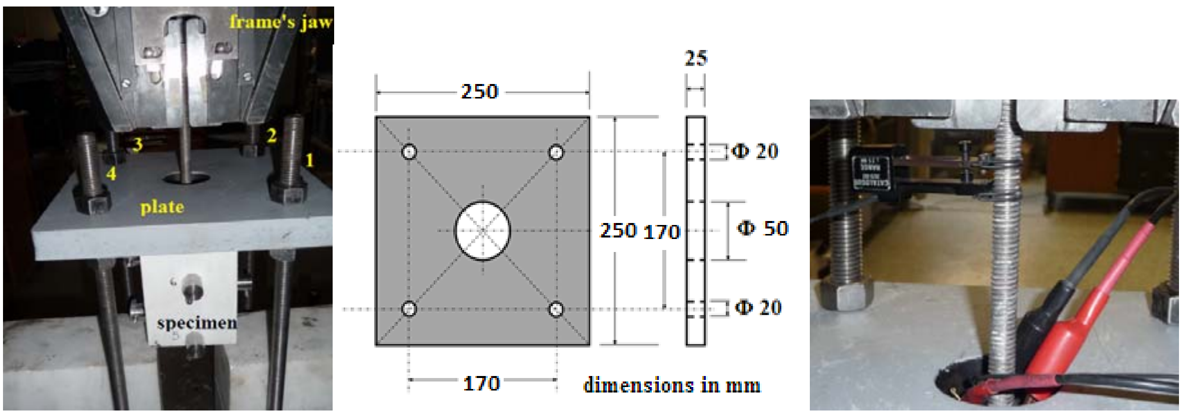

Figure 3: (a) The experiment set up, (b) The configuration of the metallic plate (c) The Dynamic Extensometer used in the experiments

During the tests, the relative displacement of the bar with respect to the marble prism was measured and recorded using a calibrated LVDT (Linear Variable Differential Transformer) touching the bar's lowest end through the cube's bottom face (Fig. 4 (a), (b)). Furthermore, in order to monitor the whole system's deformation and determine the actual movement of the bar, three additional LVDTs were placed at the bottom of the rigid plate (Fig. 4 (c)).

Figure 4: (a) The LVDT's position schematically (b) The lowest end of the cube (c) The LVDTs' positions under the rigid metallic plate.

In the experimental procedure, two innovative sensing techniques were employed, namely the Acoustic Emission (AE) and the Pressure Stimulated Currents (PSC) ones. So far, it is proven that these two techniques, when applied to brittle materials, can successfully detect cracks and damages at the material's interior while providing consistent pre-failure indicators [5, 6].

AE is based on the detection and record of transient elastic waves which are produced when the stress field developed exceeds (either locally or globally) the material's critical limits resulting to damage. The sudden release of energy accompanying damage produces waves which propagate spherically outwards until they are captured by a number of acoustic sensors, properly mounted on the specimen's surface [7]. In the present experimental protocol, eight acoustic sensors were attached on the marble surface, as close as possible to the area where the acoustic signals were expected to be produced, permitting 3D detection (Fig. 5(a)).

On the other hand, the PSC technique is based on the detection of weak electrical signals produced during the formation and growth of micro-cracks inside rock-like materials [5, 6]. For the PSC recordings two electrical contacts were placed in the specimens. The first one was embedded in the cement paste before its curing while the second one was inserted in a short predrilled hole (of depth equal to 1cm) on the marble (Fig. 5(b), (c)). The main goal is the accurate recording of electrical signals produced on the marble-cement paste interface.

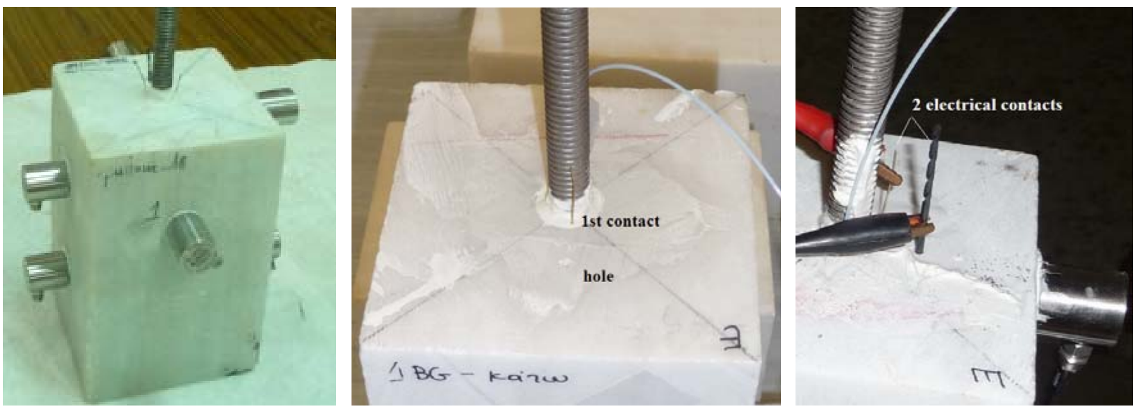

Figure 5: (a) The acoustic sensors on the marble surface (AE) (b), (c) The electrical contacts (PSC).

Observing macroscopically the fractured specimens, three main failure modes were distinguished, depending on the composition of the cementitious paste: pull-out of the titanium bar, fracture of the marble prism and failure (fracture or yield) of the titanium bar (Fig. 6 (a), (b), (c)). Taking into account the aim of the present study, attention is restricted from this point on to the tests for which the marble cube and titanium bar remained intact while the bar was pulled out.

Figure 6: (a) Pullout of the bar (b) Marble's fracture (c) Bar's failure.

2.3 Results

Typical results from experiments in which pure pull-out was observed are presented in Fig. 7(a), where the variation of the load is plotted versus the bar's axial strain. The differences observed, concerning the maximum load attained are significant and could be well attributed to uncontrollable parameters related to the inhomogeneity and anisotropy of Dionysos marble [8, 9], which dictate marble's response. On the contrary, the differences observed for the overall stiffness of the system (namely the slope of the load - axial strain curve) are rather negligible.

The pull-out phenomenon is typically described by the load-bar's displacement curve. Such a typical curve is shown in Fig.7b. It consists of an almost linear initial portion (until slightly before the maximum load) followed by a well distinguishable non-linear portion till the maximum load. A decreasing branch follows the peak force, the slope of which decreases gradually.

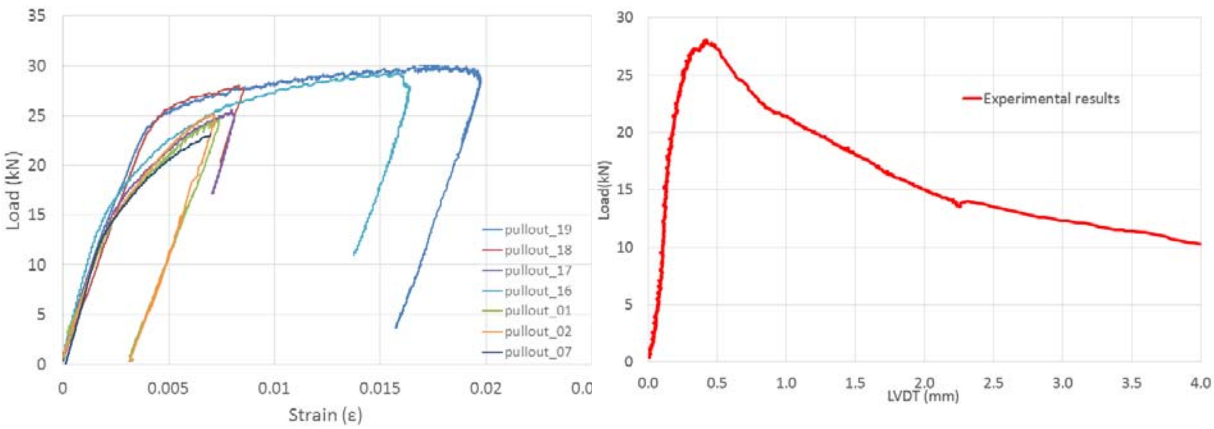

Figure 7: (a) Load vs bar's strain (b) load vs bar's displacement.

3 NUMERICAL ANALYSIS

The numerical model designed to simulate the pullout experiments was developed using the commercially available finite element software ABAQUS [14]. The specimens and the experimental procedure were simulated in every detail, to achieve optimum reproduction of the tests.

3.1 Model's geometry and materials' properties

The models consist of three bodies, i.e. the threaded titanium bar, the cement paste and the marble prism. The dimensions of the prism are the same as those of the tested specimens (Fig. 8 (a)). The geometrical characteristics of the threaded titanium bar are shown in Fig. 8 (b).

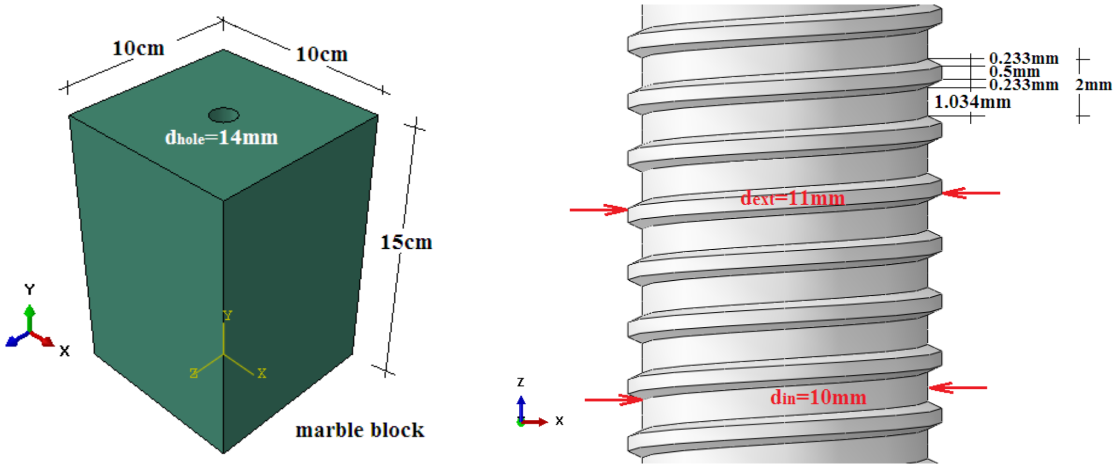

Figure 8: (a) Dimensions of the Marble block (b) Thread characteristics.

The second step of the numerical analysis is the identification of the mechanical properties of the three materials. For the Acropolis monuments, Dionysos marble is almost exclusively used since it is considered the material most compatible to the authentic building stone (i.e. Pentelic marble). It is characterized by two principal anisotropy directions (parallel to the material layers and normal to them) thus appearing to be transversely isotropic. Moreover, it is slightly non-linear and bimodular, i.e. its elastic modulus in compression exceeds slightly that in tension [8-10]. For the sake of simplicity, these features were here ignored and Dionysos marble was simulated as linearly elastic and isotropic. Its modulus of elasticity was set equal to E_m=84.5 GPa, its Poisson's ratio equal to v_m=0.26 and its density equal to 2.78 gr/cm^3.

Titanium was modeled also as linearly elastic (given that the loads to be imposed produce stresses well below its linearity limit) and isotropic material. Its modulus of elasticity was set equal to E_t=105 GPa, its Poisson's ratio equal to v_t= 0.32 and its density equal to 4.51 gr/cm^3.

Finally, with regard to the cementitious paste interposed between marble and titanium, it was considered, also, as linearly elastic and isotropic material with modulus of elasticity equal to E_p=15.4 GPa, Poisson's ratio equal to v_p=0.26 and density equal to 1.70 gr/cm^3 [11-13].

3.2 Contact properties

As already mentioned, previously reported experimental data, have definitely indicated that the most common failure mode in pullout tests was the debonding at the paste-marble interface [9, 10]. For this reason, the metallic bar in the model was considered perfectly bonded to the cementitious paste (obviously the threaded geometry of the bar is considered to play a significant role in this direction). Consequently, the overall behavior of the MTC complex is here dictated by the failure of the intermediate interface, i.e. that between marble and paste.

In ABAQUS practice, in case of bonded interfaces the thickness of which is negligibly small, the response of the cohesive layer is defined directly in terms of traction versus separation [10]. The available traction-separation model assumes an initially linear elastic behavior, which is followed by the initiation and evolution of damage. When the damage initiation criterion is met, the resultant behavior of the interface follows a damage evolution law. There are two alternative choices available for this law in the traction - seperation space, i.e. linearly or exponentialy decreasing. The respective curve is schematically shown in Fig. 9.

Concerning the initiation of damage the ABAQUS software provides four main criteria: The maximum nominal stress, the maximum nominal strain, the quadratic nominal stress and the quadratic strain [14]. Regardless of the criterion that is adopted in modeling, the results obtained are the same assuming of course that reasonable compatibility laws are applied for the transition between the various options.

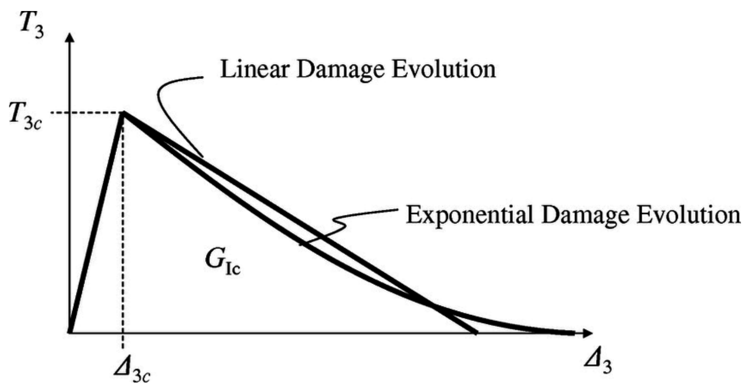

Figure 9: Schematical representation of traction-separation response [14].

4 THE NUMERICAL MODEL

4.1 Mesh density

In computational solutions, meshing is among the most significant parameters that can determine the reliability of the results. Improved mesh quality provides more accurate solutions. Unfortunately, the meshing quality is strongly related to another parameter that has to be considered, i.e. the CPU time or in other words how time-consuming the analysis is. It is generally accepted that finer meshing is related to increased computational time demands.

In this direction (and taking into account the increased number of parameters that will be investigated using the present model) the relation between the mesh quality and the CPU time was thoroughly considered. The validation of the model was achieved taking advantage of a typical experimental pull-out curve (Fig.7b). Models of different mesh densities are compared with reference to the CPU time. Four different models were constructed, for which tetrahedral elements were used for the mortar-bar complex and hexahedral elements for the marble body. The number of tetrahedral and hexahedral elements, the approximate ratio of their size and the respective CPU time for each model are recapitulated in Table 1. The mesh for the first testing case (model 01) is shown in Fig.10. The overall results of this step of the analysis are presented comparatively in Fig. 11, in juxtaposition to the respective experimental data.

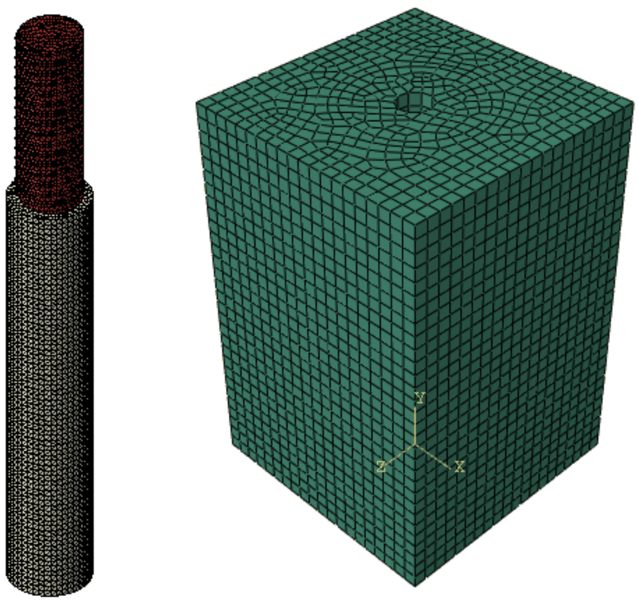

Figure 10: Mesh geometry of (a) bar-paste complex (b) marble block (model 01).

Title	CPU time (sec)	Number of tetrahedral elements	Number of hexahedral elements	Approximate size of tetrahedral /hexahedral element
Model 01	4878,8	152532	15150	1:5
Model 02	52853	352358	72350	~ 1:4
Model 03	65400	92620	93728	~ 1:2
Model 04	278673	42840	215625	1:1

Table 1: CPU time with the respective model's total number of elements.

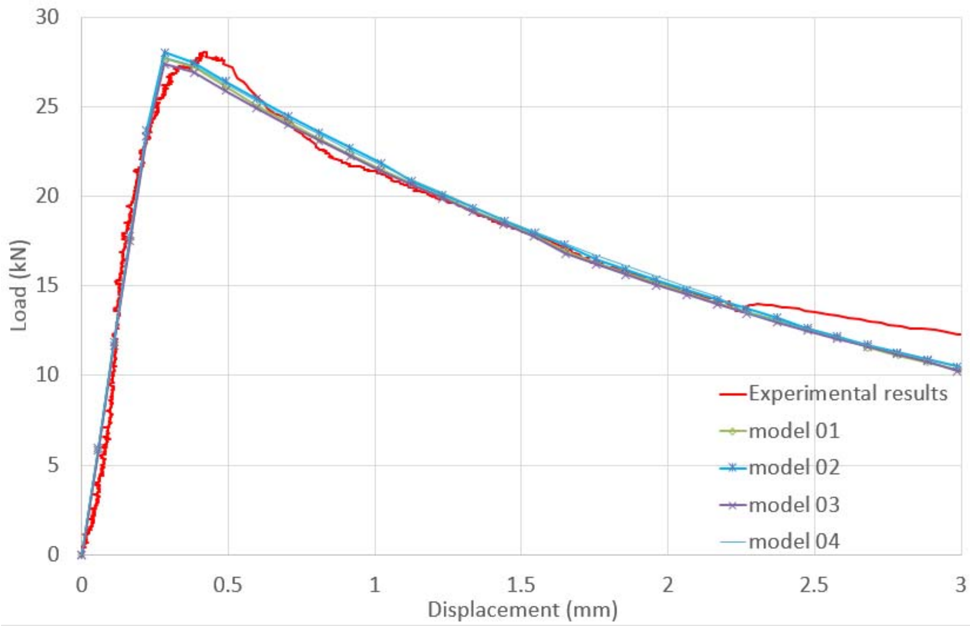

Figure 11: Load versus bar's displacement (experimental results/analyses of different mesh density).

It is definitely concluded from Fig.11 that all four numerically obtained curves are very close to each other. Moreover, their deviation from the experimental data is relatively small, despite the quite significant differences recorder for the respective CPU times (shown in Table 1).

4.2 Time increment analysis

In ABAQUS Standard, the overall convergence rate and the robustness of the progressive failure simulation of composite structures is significantly affected by the time increment of the analysis: Low time increment may give more precise results but it increases the CPU time.

For the model that was considered as the optimum one according to the results of Section 4.1 (i.e. model 01), three different time increments were considered in this step (Table2).

Title	CPU time (sec)	Time increment
Model_01	42584	0,001
Model_02	4878,8	0,01
Model_03	1508,8	0,1

Table 2: CPU time with the respective time increment.

The results of the analyses are given in Fig. 12. The larger time increment (blue curve), characterized by fewer integration points, results to deviations from the experimental data around the peak force, which may be proven critical. The medium (model_02-black curve) and fine time increments (model_01-yellow curve) provide identical curves but they differ significantly in their CPU time (Table 2). The model with finer time increments is almost 10 times more time-consuming compared to the one with medium time increments. Taking all these into account it can be concluded that the model with medium time increment is the optimum choice.

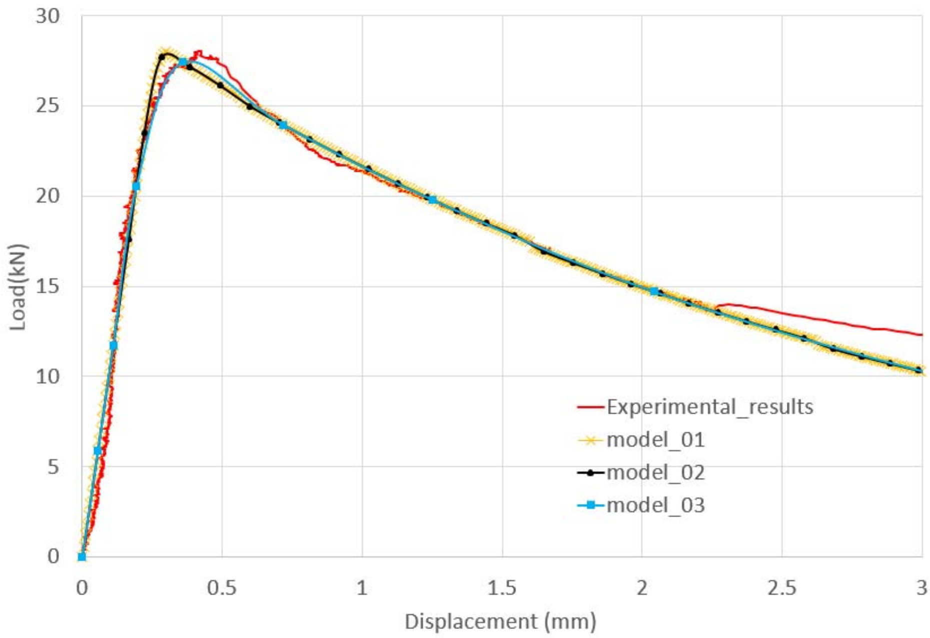

Figure 12: Load versus bar's displacement (experimental results/analyses of different time increment).

4.3 2D versus 3D models

In numerical simulations, it is important to achieve the required accuracy in the minimum possible computational time. The symmetry characterizing the specimens of the present experimental protocol permits the design of simplified numerical models, significantly decreasing the CPU time. In this direction, an axisymmetric model (with respect to the central symmetry axis of the configuration) was designed, as it is shown in Fig. 13. It is worth noticing that the computational time of the axisymmetric model is almost 10 times less than the computational time of the respective 3D one while the results seem to be well comparable (Fig. 14).

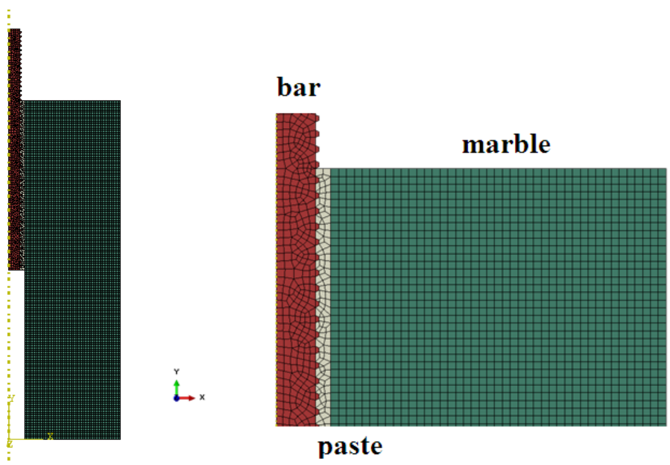

Figure 13: Axisymmetric model of pullout test

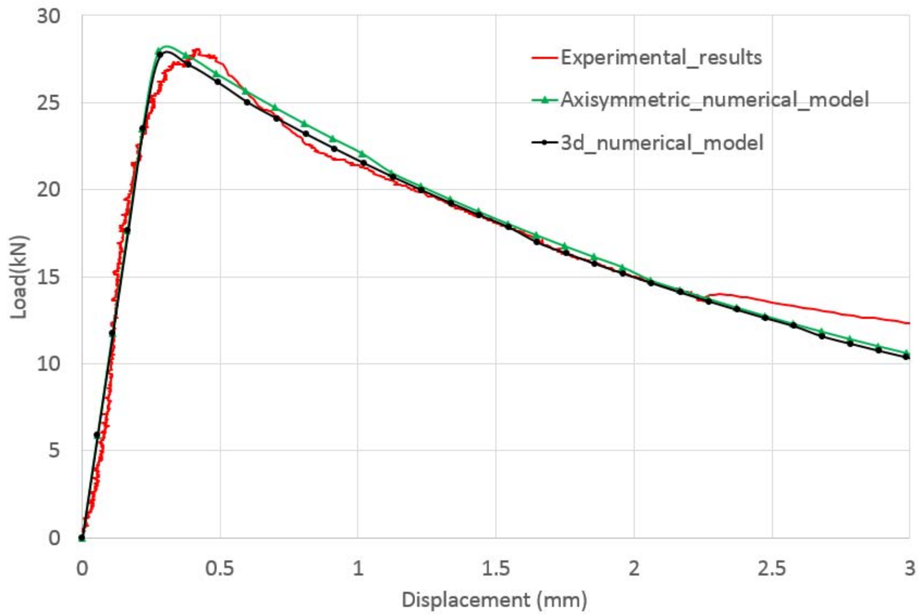

Figure 14: Load versus bar's displacement of axisymmetric and 3d pullout model.

5 DISCUSSION AND CONCLUSIONS

A finite element model was designed that will be used for the parametric study of the pull-out phenomenon observed in restored marble structural members. The model was calibrated according to the data gathered from a specially designed non-standardized experimental protocol. At this point the question could arise related to the accuracy and reliability of the experimental data themselves. In an attempt to eliminate such doubts the data of a typical test, as they were gathered by three different sensing techniques, are plotted in Fig. 15. More specifically the relative displacement of the bar with respect to the marble prism (as recorded by the respective LVDT) is plotted against the load level in conjunction to the cumulative electric load Q (as determined using the PSC technique) and the cumulative energy of the acoustic events (as determined by the AE technique). It is very intersting to observe that the data gathered by all three techniques are in excellent mutual qualitative agreement. In depth analysis of these data has proven that they are also in very good quantitative agreement [15], enhancing confidence to the reliability of the experimental results used to validate the numerical model.

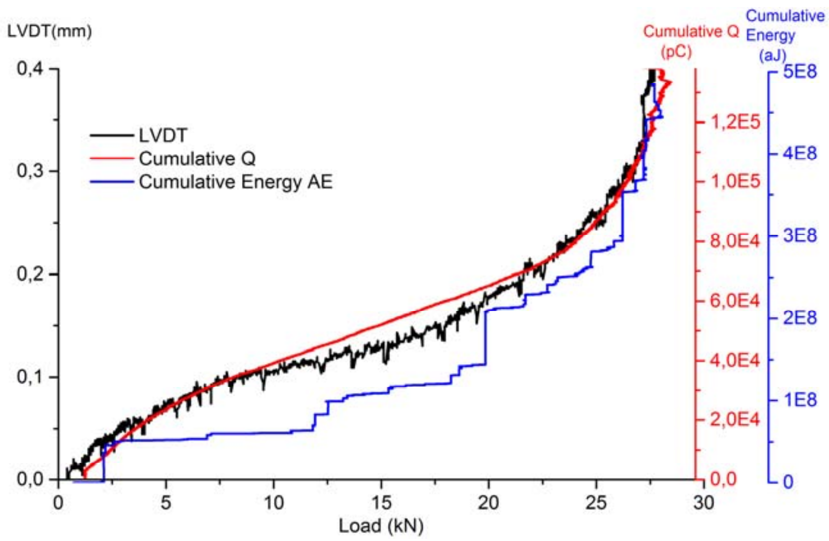

Figure 15: Comparative representation of the data gathered by the LVDT, the PSC- and AE-techniques.

The model designed was optimized in relation to two crucial aspects, i.e. meshing and time increment of the analysis. A satisfactory compomise between accurracy and CPU time consumption was achieved. Morever the model's effectiveness was assessed in case a simplified axisymmetric design is chosen against the "heavier" three dimensional version. It was concluded that the diffrences are rather negligible and, at least for this specific application, no reason exists to use three dimensional analysis.

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