NUMERICAL STUDY OF THE STABILITY OF RESTORING DAMAGED SCULPTURE

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Abstract

Actors working on the preservation and restoration of the cultural heritage use more and more efficient tool for restoration design and execution. In the last few decades, the development of modern digital tools for structural analysis offers new strategies and opportunities for this community. (Borri 2006; Coignard 2009)

Numerical analysis of structures could be used as an associated method in the field of cultural heritage conservation. In the present work, mechanical 3D simulations were used to, a posteriori, evaluate the restoration technique performed on a Roman marble sculpture, the Neptune statue. This artwork founded during underwater excavations of the Rhône River in 2006 was broken into four pieces. The restorer (Coignard 2009) used a laser scanner for geometry acquisition of sculpture blocks. The resulting cloud-points were then introduced in CAO for the virtual reconstruction and a first evaluation of stability using a simplified static analysis.

The same cloud-points and model geometry are used for the methodology developed where the 3D mesh assembled is used as an input for mechanical simulation software.

Thanks to numerical techniques used, the damaged sculpture can be reconstructed, assembled and the efficiency of alternative reinforcing techniques can be evaluated.

Our first results depict the key role of interfaces in the overall behavior of the assembled sculpture. Experimental studies on the actual behavior of fractures in blocks of statue's material allowed us to calibrate our model. Some parametric studies on the tie rod prestressed force and contact interfaces parameters show the influence of these elements on the final stability of the statue.

Keywords: restored sculpture, static analysis, numerical modeling, interface, mechanical behavior

1. Introduction

Cultural heritage is a recent concept: UNESCO creates in 1956 ICCROM (International Centre for the Study of the Preservation and Restoration of Cultural Property). Artworks are included for the first time in cultural patrimony. Then, in 1964, the well-known Venice Charter (Venice Charter 1964) offers a real enhancement for conservation which focuses on monuments, sites and excavations. This latter is also the first charter to establish the goals and limits of the restoration as well as the ethics, historical and aesthetic notions. Further, the Krakow Charter (Krakow Charter 2000) based on the Venice Charter was born. The ideas of history and aesthetics are retained, definitions of conservation and restoration of built heritage were reminded, and authenticity notion is approached. However, the charter insists in the way that the restoration should remain a limited action and on the responsibility of restorers. Moreover, the charters define restoration as an extraordinary action, only when artworks are in danger and the restoration work should set the subject in the previous known state. Collaboration between the cultural heritage community and scientific engineering is a fairly recent development. For instance, some projects have emerged in the domain of the cultural conservation of buildings, e.g. (Kourkoulis 2009, 2010a, 2010b) or that of risk studies of some famous sculptures (Borri 2006). Kourkoulis checked numerically the static and dynamic stability of damaged structures such as the epistyles of the Parthenon (Kourkoulis 2010a; Stefanou 2011). In that case authors dealt with the problem of interfaces between structural elements and inserts and those among stone blocks and mortars.

In the field of sculpture restoration in France, at the best knowledge of these authors the first artwork digitalization was carried out in the framework of CAMILLE program (French Ministry of Culture) under the direction of Schmitt (1993) with the restorer R. Coignard for the reproduction of the Gaulois Warrior of St Maur, a hammered brass statuette which cannot be molded by traditional processes because of its fragility. Coignards' restorer developed a methodology including digitalization technology of the broken parts, virtual reconstruction of statue, static stability analysis, and conception by simulation of the restoration process, for the restoration in 1994 of the Emperor Augustus statue from Arles museum (Coignard 1997) and Ptoleme statue (known also as Colossus of Alexandria) in 1998 (Coignard 1998, 1999). In this last work numerical simulations have also been performed using finite element software (Code Aster, EDF). Recently, using this technology for the restoration of Neptune statue has been successfully performed (Coignard 2009).

The research program REPTURE, involving academics (PRISME and the CRMD laboratories of Orléans University) and cultural heritage actors (Coignards independent patrimony restorers) aims at continuing of pioneering idea of restoration of broken statues using digitalization and numerical analysis of stability based on a scientific methodology.

This methodology consists in scanning all parts of a broken statue to obtain the corresponding discretized volumes, in modelling of geometry, proposing alternative restoring solutions from restorer, evaluating and optimisation of alternative solutions in respect with short and long term stability of restored statue and reversibility of restoration. The numerical tools used for evaluation of restoring solutions correspond to commonly used software so that the methodology can be used by non-specialists.

In this paper this methodology is illustrated using the already restored statue of Neptune (Coignard 2009). Firstly the approach commonly used on the restoration of broken statues including scanner digitalization, rigid corps stability analysis and restoring solution is briefly presented (interested reader could find more details about this work following this link www.sculpt.fr). Then numerical analyses performed in the framework of REPTURE program are presented and discussed in respect with the role structural elements on the overall stability.

2. Restoration of a broken statue using rigid solid approach: Neptune's restoration (Coignard 2009)

Figure 1. Restored Neptune Statue

The example described in this first part is an illustration of the methodology carried out for the restoration of broken statues using scanner digitalization and a simplified geometrical modeling based on hypothesis of rigid solids (Coignard 2009). All illustrations in this section are due to the above mentioned reference.

The Neptune statue is a Roman marble whose restoration was entrust to Coignards' sculptures. The restored statue was shown during the temporary exhibition: Arles, Record of the Rhône, Twenty years of underwater excavations on the Louvre museum in Paris and can be found, commonly, in the Arles Antique Museum.

This statue was found in 2007 by a sub-aquatic team of archaeologists on the Rhone river. It was certainly a present from the Arlesians Boatmen corporation. It measures about 1.60 meters and was made with a Greek marble from the Penteli mount toward 160-180.

2.1 Geometry acquisition and simplified stability analysis

Following this methodology, the numerical reconstruction of the statue is performed to carry out the analytical mechanical calculation. Therefore, the artwork model is used by the restorer in order to infer restoration constraints and to design the appropriate solutions for the restoration. To this aim, in the first step, the artwork pieces were put together by the restorer to visualize the blocks assembly and the breaks inclination and to check the good interlocking (Figure 2b). To construct the 3D model of the statue, all blocks are scanned using a Konica-Minolta laser scan (VI-910) which provided the surface cloud-points of the sculpture (Figure 2c). Each block of the statue presented to the laser scan was carefully rotated through 360° such that the whole block's surface could be scanned and it is often necessary to make several captures from different points of view. All scanning files are then assembled by algorithms analyzing the similarity of the commune zones then merged in a single file defining the closed geometry of a block. A particular attention is applied for the quality capture of broken zones surfaces which are the interfaces between the different parts of the statue. Upon the precision of their definition will indeed depend the accuracy of their association so that the virtual reassembly of the statue is in accordance with the reality of the original artwork.

The second stage of this methodology (Figure 3) is the determination of the weight and the centers of gravity of each block and the assembly of these blocks. So, the preliminary virtual reassembly defined the vectors of gravity of the whole of successive blocks to measure their incidence on the lower blocks (the vector of the block of the head, then the association head / trunk, and finally of the association head / trunk / knee) to carry out a graphic analysis of static stability of the statue. An overhang was observed showing that the vertical axis of the vector of gravity of the higher blocks in supports on the knee passes tangentially outside the leg. The application of this methodology leads to some alternative solutions such as:

- a single metallic insert of a big section from the top of thigh to the calf,
- an external prosthesis for the missing leg maintaining the left knee, but difficult to plan because of the visibility on this historical artwork and the dilatation of this part,
- a metallic tie rod which only works in tension and cannot, in that way, applied stress inside marble, except at the anchorage length. With this solution, no more than surface's breaks were solicited.

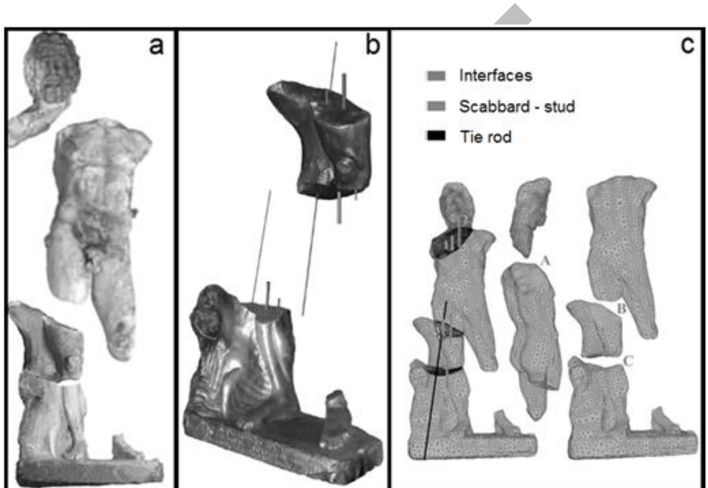


Figure 2: Blocks of the broken sculpture (a) and numerical model of the reinforced statue (b, c),

Figure 3: Restorer calculation as rigid solids, gravity vectors of blocks and those of their stacks

So a pull cable was conceptualized. In order to guide and to facilitate the blocks assembly during the restoration act, studs were also chosen. More precisely, at each break position, one stud was used to guide while another were put to forbid the rotation between blocks. In additions, to make easier their insertion, they must be parallel. On the top inclined break, the double studs solution was selected because as it induces good resistance in a tangential way. The calculation part of this methodology conducts to determine weakness areas on the virtual assembly that require reinforcements. The process used allows the restorer in a simplified way to bypass difficulties of the achievement of heavy calculations. The experience of the restorer allows him to conceptualize metallic inserts and to obtain a good approximation of their optimal locations. However, without data concerning mechanical analysis of the stability and the resistance of each structural element, the knowledge and the abilities of the restorer are of capital importance for a successful restoration.

2.2 Details of restoration mechanism

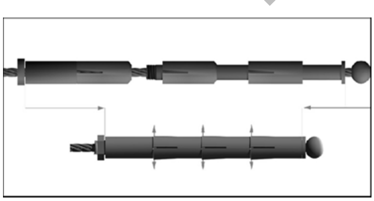


Figure 4: The pull cable anchor

For the sake of the completeness the mechanism of cable anchorage is described here. The anchor of the pull cable must resist to the pretension stress. An expansion anchors compressed with a screw and bolt leads to an increase of the piece diameter and induces the anchorage strain (figure 4).

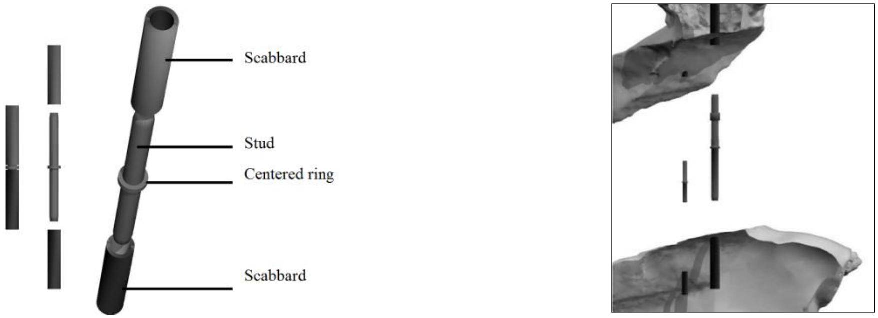


Figure 5: Studs geometry and studs were put on breaks according to (Coignard, 2009).

Each insert used comprises a stud and two scabbards (Figure 4). Scabbards are glued in the rock mass by a bi-component glue on hole drilled on the stone. Then stud are inserted in scabbards and bear on the central ring. It must be mentioned that no verification could be made with this simplified approach whether the marble could support or not the local stress of anchor.

2.3 Remarks on rigid solid approach restoration

As shown by this example, following this approach some critical problems during restoration process are resolved by an empirical while some of these questions could have a scientific response. In particular, the restoration is performed with the hypothesis that at any point, thanks to the implementation of the prestressed cable, the internal stress induced either by the superposition of blocks or by inserts is never beyond the stone strength. Likewise the contact surfaces of blocks of a broken statue often are weathered and the imperfect contact could be a source of stress concentration neglected by this approach.

3. Methodology of restoration based on numerical analyses

In this part a second methodology is presented based on detailed numerical analyses of the stability. It is used here to verify the Neptune stability after restoration but more widely, it offers a systematic way to gage restoration projects. While the geometry reconstruction would be identical to that already proposed in the previous method, in order to perform numerical analyses, a volumetric mesh of all blocks of the statue is now necessary. Beside, one needs to take into account in some ways the elements of reinforcement for the numerical simulation purpose. It is worthy to note that the modeling of these inserts and also the interfaces between the fragmented pieces of the statue is a difficult numerical task which could significantly contribute to the predictive behavior of the reinforced statue and the success of the developed methodology. In respect with the software one disposes and the importance of the interfaces and inserts one could use models more or less sophisticated. Numerical modeling of bolts, cables and joints are widely applied in geotechnics (Lefèvre 1997; Grasselli 2005; Li 1999; Dias 2011). This explains why some of numerical tools used in our work are closely connected with such geotechnical problems.

2.4 Modeling of the reinforce elements and interfaces

The cloud-points used by the restorer to perform preliminary calculations was reused to get the three dimensional mesh of the statue after CAD processing.

Several ways can be followed to introduce reinforce elements in the model. The simple way is to consider them as structural elements in 1D, as it is usually the case in engineering modeling practice. Of course a more sophisticated model of 3D could be envisaged. In this paper, the former strategy was adopted. Not only this choice leads to a less time consuming numerical approach, but it also allows correct representation of the physical behavior of inserts through rigidity of element that takes into account the geometry of inserts section. Besides, the implantation of the inserts in the volume of the sculpture is much easier in this case with the help of the Flac3D code (Fast Lagrangian Analysis of Continua in 3 Dimensions) developed by ITASCA (Itasca Consulting Group 2006). Indeed, many structural elements such as beam, cable, pile and interface elements are available in this code which facilitates the modeling procedure. In the practice, the 1D structural elements can be easily adjusted in the model by specifying the position of different nodes. They are then attached to the volumetric 3D model of the statue through a system of linkage between the element's nodes and the mesh of reinforcing elements.

For the Neptune statue reinforcement elements contains five pile elements (modeling studs) and a cable element of Flac3D (modeling the pull cable in the statue). Also, in Flac3D, the 1D cable structural element is associated with the 3D structure through a set of nodes which are modeled as a spring - slide system characterizing the shear resistance of the grout between the cable and rock mass. Their properties describe the grout stiffness, the grout cohesive strength, the friction angle and the exposed perimeter of grout. The interface between tie rod anchoring and stone is represented by the shear behavior of the grout annulus which is frictional and cohesive in nature. Thus the cable element can sustain the tension and compression forces. In addition, the pre-tension force can also be taken into account in the cable element which is maintained by the anchorage length located in the torso block and maintained under the lower block.

The important difference between the cable and the pile elements (which represent the five studs) is that the latter can also support bending moments and some additional features which can account for the normal behavior of the pile - grid interface. This interface, also simulated by a spring-slide system located at each node along the pile axis, is described numerically by the normal coupling spring properties which are the stiffness, the cohesive strength, the friction angle and the exposed perimeter.

Finally, to model the contact between the fragmented pieces, interface elements are defined on meshed surfaces. In Flac3D the contact takes place between the interface nodes and a surface zone known as the target face. These contacts are hence detected only at interface nodes. Moreover, the associated model is defined by a linear Coulomb shear-strength criterion. Consequently, the interface elements are characterized by their properties which consist in friction angle, cohesion, dilation angle and normal and shear stiffness. In Figure 2c three interfaces between four fragments of statue were well illustrated.

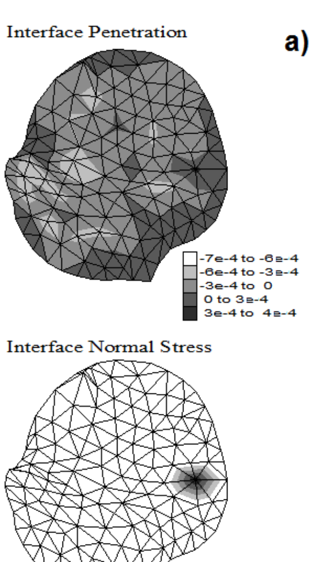
2.5 Results and discussions

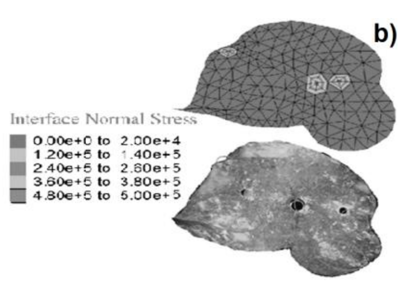
As no experiments have been conducted on the materials of the statue, most of mechanical properties used in the simulation are taken from the literature. Parametric studies are performed to determine the impact of variation of parameters on the final behavior of the restored statue. The parametric study is performed on the parameters for which uncertainties are very large or there are no available values or the values found in the literature vary by several orders. These parameters are the shear cohesion of the cable (the cohesion at the interface between the prestressed cable and the rock mass), the normal cohesion and the normal stiffness of the pile element.

As shown in Figure 6a, the penetration of the interfaces generates different points of contact at interfaces. These results seem to be in good agreement with the observation realized during the assembly of the restored statue where only points of contact were stated. Nevertheless, comparing these results with photographs of tagged interfaces, it appears that these points are quite differently located (Figure 6b). The numerical position of blocks differs from the original position, which may explain this difference. However, it is important to notice that the maximum stress observed on the interface is about 0.9 MPa. Moreover, Figure 6c shows the interaction of the anchorage of pull cable and its environment (the marble of the statue). Also, the concentrated stress at this level is not prejudicial to materials. The maximum value of the compressive stress obtained is of 0,5 MPa, while Dionysos marble can withstand to a stress of 90 MPa (Papamichos 2006); obviously the metallic anchoring of the pull is not an area of weakness.

In Figure 7, vertical displacements of blocks in Y direction are represented on the right (Y axis follows the feet-head direction of the statue) while horizontal displacements of blocks are on the left. Under the influence of its own weight the torso switches to the left and back and also pivots around the vertical axis of the statue, taking with him the head and the knee. While, the head moves along the inclination of the upper interface. Figure 7 shows that the maximum displacements are on the block head with values of 2.3 mm for the vertical displacement and 1.8 mm for lateral movement. Moreover, the stress on inserts is small and represents about 20% of the metallic yield strength.

The numerical simulations carried out demonstrate the stability of the restoration of the Neptune statue. Through various parametric studies, it shows that the stress in the statue as well as in the reinforce elements remains in all cases far below to the elastic limits of materials. It shows otherwise that for the static behavior studied here, the structural reinforcements are largely oversized.





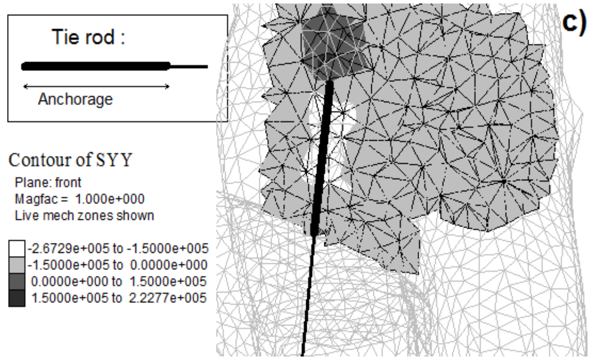


Figure 6: Shear stress and penetration at interface B (a), Comparison between normal stress calculation and a photography with frictional area (b), Stress in the longitudinal section passing through the axis of the cable element (c).

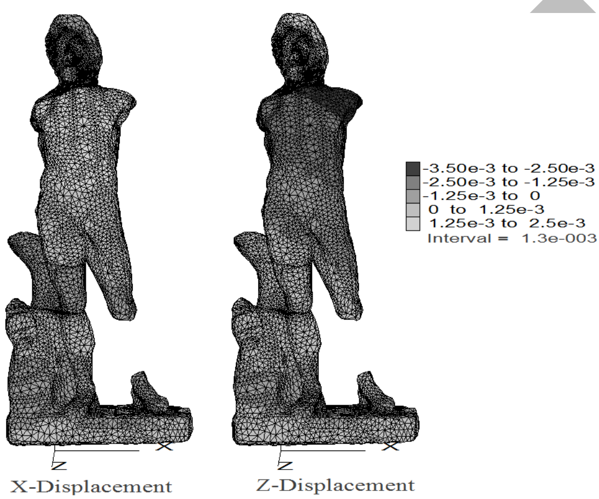


Figure 7. Vertical and horizontal displacements

4. General conclusion

In this work, the application of numerical tools to study the behavior of restored sculpture is conducted. This numerical modeling allows to calculate the stresses transmission between the different blocks and the metallic inserts through their respective interfaces. The behavior of the statue's blocks assembly and its restoration seems coherent with reality, particularly at the interfaces.

This approach is assumed to be an efficient method that could help the restorer to diagnose and to make the best decision concerning restoration. The systematic methodology is used to evaluate a restored Neptune statue. Different steps of geometric construction, meshing and numerical calculation demonstrate the accuracy of the carried out restoration and the structural reinforcements are largely oversized. However, the numerical modeling does not provide details about the local behavior of inserts or of the rock mass at the level of contact. To overcome this limitation, more refined insert modeling is required.

5. Perspectives and ongoing works

While simplified modeling gives an insight on the efficiency of restoration method a more detailed model is necessary to evaluate local impact of inserts. Such a model is currently in progress, where the 3D geometry of inserts will be explicitly modeled by using a CAD package. This needs modifications on how to construct the geometry model from cloud points (Ramos Barbero 2011) using more sophisticated CAD techniques to create the final geometry before meshing it. Finally, the results of the latter step furnish the input to a Finite Element Analysis code to carry out the calculation. With this approach the geometry of the system will be described in detail but a greater number of parameters are necessary for modeling.

Mechanical properties of the marble (particularly at interfaces) and those of the expansion anchor are being identified from tests in progress. Shear tests will be conducted on Dionysos marble from Greece and pull-out tests will be conducted on a duplicate of the expansive anchor used in the restoration of Neptune.

The next step of this work will be to apply this methodology to study the dynamic behavior of a damaged sculpture.

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