IOP Conference Series: Materials Science and Engineering

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To cite this article: M Bici *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **364** 012014

IOP Conf. Series: Materials Science and Engineering **364** (2018) 012014 doi:10.1088/1757-899X/364/1/012014

CAD-CAE methods to support restoration and museum exhibition of bronze statues: the "Principe Ellenistico"

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Abstract. Ancient bronze statues mainly require material integrity assessment and restoration. Restoration may include also the update of the museum exhibition, defining new structural frames and fragment re-composition to preserve the statue and improve the interpretation of the original aspect. This paper proves how engineering methods (such as Finite Element Analysis, Computer Aided Design modelling, Reverse Engineering) may assist cultural heritage experts and restorers in these tasks. It presents the activities made together with the Museo Nazionale Romano and the Istituto Superiore per la Conservazione e il Restauro, on the so-called "Principe Ellenistico" (Hellenistic Prince). This bronze was found in pieces (body, left arm and right leg), at the end of 19th century during an excavation made in Rome. No visual or reference sources can say its origin and its final posture was defined by restorers at the end of the 19th century according to their hypothesis and studies. In the 20th century, a further restoration was made on the critical areas of the surface, together with some structural improvement of the inner frame. Nowadays, after a review of its position inside the Museum, new experimental and numerical analyses have been carried out to better understand surface weakness and correct left arm positioning.

1. Introduction

The conservation of archaeological bronze sculpture in Italy has evolved in several phases. During the 19th century, the main focus was the reconstruction of the formal integrity of the sculpture by reassembling its fragments and fractured elements and the integration of missing parts. Examples of this approach are the bronze statues found at Pompeii and Herculaneum now at the Archaeological Museum in Naples, and the "Pugilatore"(Boxer) and the "Principe Ellenistico" (Hellenistic Prince) both in the Museo Nazionale Romano (MNR), and the statue of Treboniano Gallo, Metropolitan Museum of Art, New York [1,2]. Starting from the second half of the 20th century, attention shifted towards preserving the integrity of the surface layers, by investigating the compositional elements of the original surface and studying preventive methods for the stabilization of corrosion processes and the preservation of ancient patinas that would at the same time respect and enhance the appearance of the sculpture [2]. Thanks to the establishment in the 1940's of an Institute for Conservation (Istituto Centrale del Restauro, ICR), strongly inspired by the ideas of Giulio Carlo Argan, and founded by Cesare Brandi, a new concept of 'preventive conservation' was defined and described in the publication of Brandi's 'Teoria del Restauro' (1963), where methods of conservation were defined in a systematic treaty, [3,4].

In the 1970's, important discoveries of ancient bronze statues such as the Riace bronzes, and conservation interventions on other bronze sculptures present in Museum collections (the Cartoceto bronzes and the Dionysus of the MNR) or originally exposed outdoors (The San Marco horses and the

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Colossus of Barletta), generated the opportunity of applying innovative non-destructive diagnostic methods along with traditional chemical analysis, initiating new strategies capable of identifying compositional elements and, at the same time, defining new methods of preventive conservation and monitoring with non-destructive procedures.

During the same period the artisanal techniques and reconstruction methods of the 19th century were replaced by new reassembling methods involving reversible materials and new technological approaches. Innovative solutions were developed at the end of the1970's by researching and designing internal support systems. These new support techniques were used for the Selinunte Ephebus and the Eros of the MNR. These solutions are still widely adopted today to connect the fractured parts of large sculptures and for the creation of static base elements for sculptures with a limited ground support area, as in the case of statues who stand solely on feet soles or horses' hooves. A specific example of this application is the Satiro Danzante of Mazara del Vallo [5], where the absence of the inferior part of the body required the re-composition of the fragments over a reconfigurable frame able to sustain and secure the statue. Anti-seismic solutions have also been investigated and defined, like in the case of Bronzi di Riace and the statue of "Germanico da Amelia".

Concerning non-destructive tests and diagnostic, new techniques were applied like for example eddy current, holographic interferometry and acoustic emission. They are used to improve the accuracy of the radiographic inspection with a more detailed view of the solid parts against the cracks, and new qualitative and quantitative concerns about stress and strain distribution according to the environment agents. The quantification of the stress and the strain field has also been approached through Finite Element Analysis (FEA). One of the first studies was made on the Marco Aurelio statue to evaluate the stress field due to the gravity and the critical areas of the horse according to its preservation state. These results were correlated to experimental measurements by means of gauges, moving the knight over the horse [6, 7]. Generally speaking FEA for cultural heritage involves studies about static behaviour or seismic response of buildings, statues and their support systems [8, 9]. More recently, thanks to the enhancement of virtual modeling and shape digitalization, new applications of Computer-Aided technologies have been made. They are focused on fragment reconstruction, digital modeling for data archive and communication and numerical analysis via virtual prototyping. In particular a detailed reproduction of the restoration chronology via virtual model, together with virtual prototyping results may help the experts to assess and evaluate critical parts of a work, improving its interpretation and exhibition.

This paper concerns with this field of applications, applying a Computer Aided Engineering (CAE) approach to the ancient bronze statue, known as the "Principe Ellenistico". More in details, it reviews the chronological steps of its restoration and presents CAE analysis with the aim of assessing criticality in terms of mechanical response and evaluating how it can aid its preservation and exhibition.

2. The statue

The Hellenistic Prince, is currently placed in Rome at Palazzo Massimo, part of the Museo Nazionale Romano. It was found in 1885 on the hillside of Quirinale, Rome, probably in the ancient area of the Costantin's thermae. It is 2.040 m tall and depicts a naked hero as usually made in case of sovereigns or warlords (figure 1.a). Although its original representation is still investigated, several experts recognise it as an hellenistic prince of the III-II century b.C., carried in Rome as spoils of war.

The first restoration was made at the end of the 19th century to recompose fragments and to guarantee structural support with an ad-hoc frame. The fragment reconstruction involved front part of the right foot, right leg at the thigh (fragment found separated from the statue), left leg at the knee, left arm (fragment found separated, with lacuna). Conjunctions were made through plates of brass that were jointed to the statue transversally to cracks and edges, by brass screws (Ø 6mm). Missed parts and holes were also rebuilt and filled with bronze. The spear in the left arm is not original but added according to the final posture and iconographic studies.

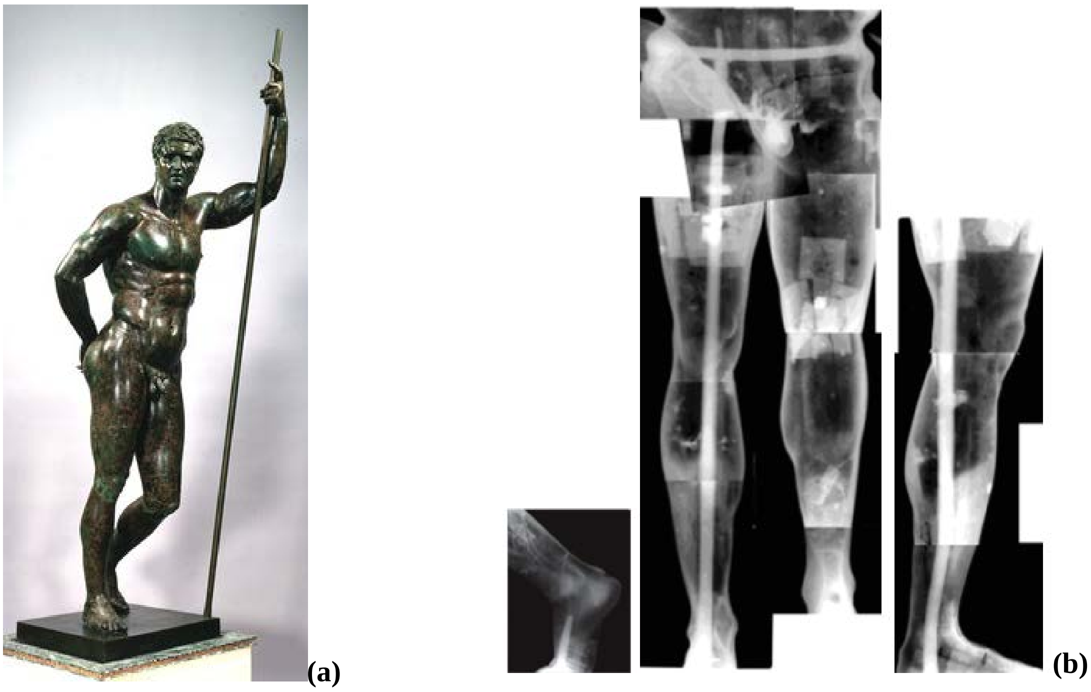


Figure 1 (a) the "Principe Ellenistico"; (b) RX for support frame and left foot

At the end of the last century, the left arm was taken apart and reviewed due to cracks along the stucco used to joint it. At the same time, a new inner support for the left arm was specifically designed; and a testing campaign was defined according to ENEA and ICR. It was oriented to evaluate chemical composition and to acquire by radiography and endoscopy bronze integrity, frame and junctions status. In 2003 active corrosion started again, mainly in form of pitting. This was approached by applying corrosion inhibitors and protective coatings. This work was carried out in 2004, in the framework of a maintenance intervention. At the present, new surface checks have been made together with the renewal of the exhibition set-up that involves a new basement and air-monitoring equipment for the room, so that climate environment changes may not have effect. In addition, CAE investigations have been planned starting from a 3D model achieved through a digital acquisition.

3. CAE investigations

Scope of CAE activities concerns with an evaluation of critical areas and a check of the posture, considering the changes made to the frame anchorage and the left arm, during the restorations.

3.1 Modeling the support frame

No technical drawings of the support frame are present, so that CAE modelling has been made according to the evaluation based on a pictorial drawing, RX shown in figure 1.b and visualization of the inlays for the conjunction. The inner frame to anchor the statue to the ground basement, is made with two bars with square section (30 x 30 mm). One is inserted in the right leg, it is rather vertical although it was bent to follow the shape of the leg. The other bar is at the hips. In addition, a pin was inserted in the left foot to connect it to the basement.

In the 19th century, the vertical bar and the pin were constrained at the bottom of the statue, filling the empty space by different kind of materials (stucco, wood,…). Filling empty space was a common practice of that period.

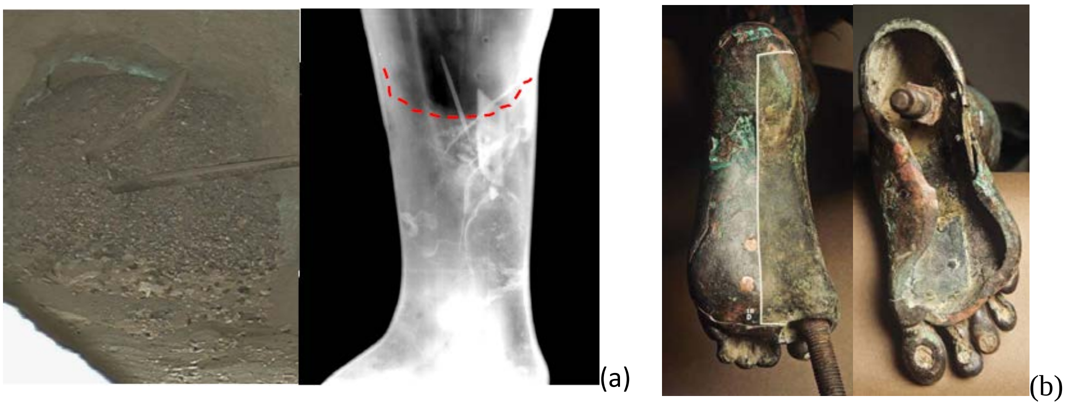


Figure 2 (a) RX and endoscopy of the filler in the left foot; (b) Details of the feet and their anchorages

At the end of the last century, the filler was removed from the right leg, whereas it was impossible for the left foot. As result, the vertical bar in the right leg may be compliant in the respect of right leg anchorage. Figure 2.b shows the details of the feet to give evidence of: (i) the small areas that are involved in the contact with the ground; (ii) the filler still present in the left foot.

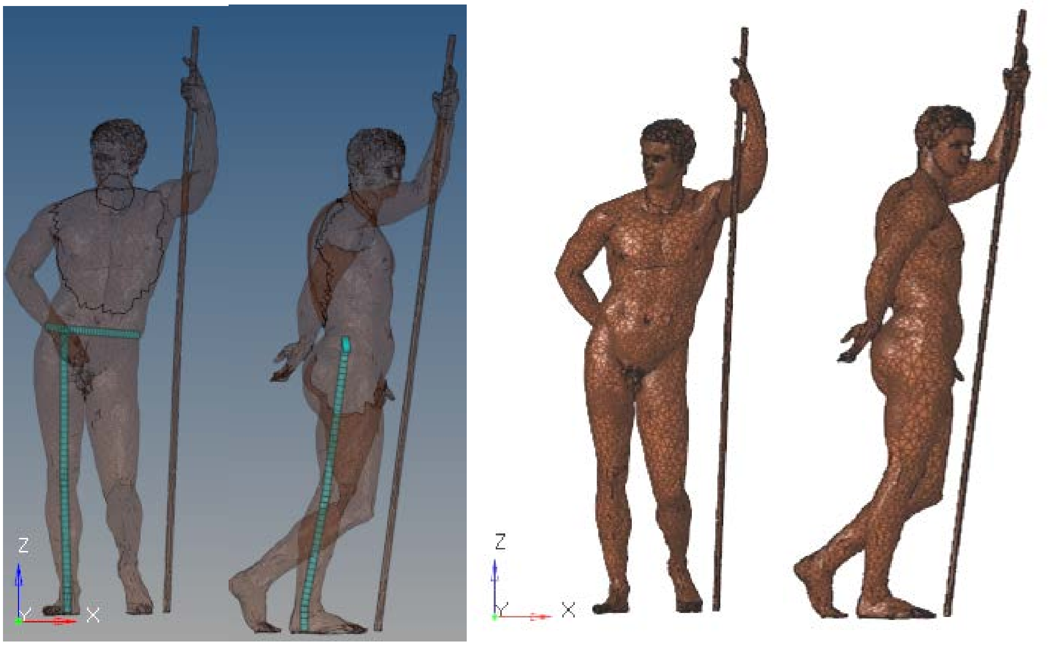


Figure 3 FEA model: support frame and statue

3.2 Modeling the statue

The surface modeling has been made starting from the digital acquisition of the bronze, made by a 3D Scanner Artec Eva. It has more than $2x10^6$ points that have been filtered, according to curvatures, so that, a triangular tessellation of about $26x10^3$ 2D elements has been achieved through Delaunay's algorithms. A restriction on the element distortion (connected to minimum length and angle) has been imposed to avoid elongated or distorted elements. Doing so, a regular mesh has been obtained, consistent with FEA mesh requirements and, finally, tessellated elements have been converted into shell elements. Figure 3, on the right, shows the results of these procedures, showing a higher density of elements in zones with high variety of features and curvatures.

The final FEA model is made by three parts: the statue, the inner frame assuming the left arm part of the shoulder, the spear in the left arm in contact, but not connected, with the forearm and the hand.

Thickness distribution of the statue has several uncertainties. Investigations have been made through ultrasound technique by ICR. In the statue, 5 major castings can be found: trunk and left leg, right leg, right arm, left arm, head. The results gives a thickness in the range of 5.0-6.5 mm. The thickest areas are that related to major details of the shape, muscles of the back (6.3±1 mm), face (6.75±0.07 mm). Considering that the overall weight without the basement is about 180 kg, we assume to investigate two configurations: one with uniform thickness equal to 5.9 mm and another with three set of thickness 8.0 mm and 6.5 mm, for the head and the back respectively, and 5.7 mm elsewhere (non-uniform thickness distribution). Major thickness has been given to the head, considering that the hair represent a part with thickness larger than the rest of the face, but extremely difficult to be measured. In this case, the weight in the upper part of the statue increases of about 24%, moving the centre of mass along the inclination of shoulders and head.

Simulations have been made using Optistruct, inside Hyperworks2017, finding both linear elastic and modal solutions. As first hypothesis, the statue has been assumed without discontinuities among the edges of the fragments, as well as the material between shoulder and left arm. Concerning the Boundary Constraints (BC) we have investigated different variants:

- BC#1: right foot in contact with ground but free in the respect of the inner wireframe; anterior part of the left foot rigid with the pin inside; no added support frame between left arm and shoulder.
- BC#2: right foot rigid with the inner support frame, up to the filler present before the 1970s restoration.

In both cases, the spear was considered in contact but not integral, so that it can react only if contact with the arm is forced.

4. Results and discussion

4.1 Static Analysis

In the case of BC#1, final displacement of the static analysis confirms the tendency towards a rotation around the axis defined by the feet. The maximum displacement is 3.56 mm in case of non-uniform thickness distribution, 3.34 mm in case of uniform thickness, that means about 6.5% of difference. Figure 4 shows the displacement field for the statue and the inner frame, in the most severe condition for the displacement (BC#1 non-uniform thickness distribution).

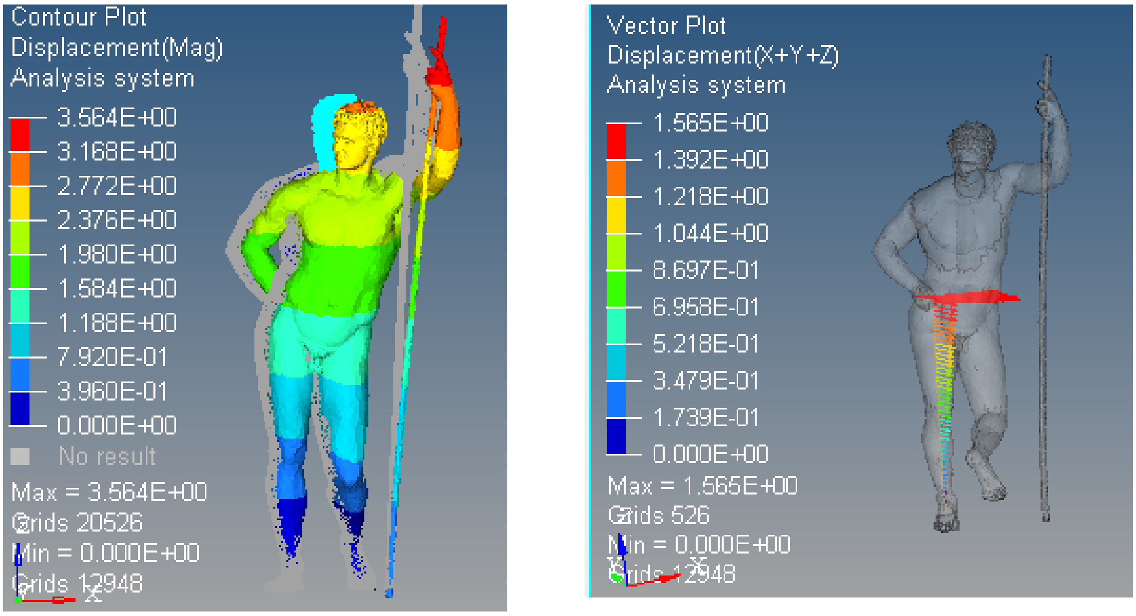


Figure 4 BC#1 with non-uniform thickness distribution: maximum displacement (units in mm) in the statue and in the inner structural frame

The spear does not react axially to the statue weight, but it is bent due to the arm rotation under load. Loads are distributed between left foot and right foot plus the frame in the ratio 2:3. Changes in thickness distribution do not change statue response, significantly.

Concerning the stress distribution, higher values are always located at the feet. A quantification of the stress level is shown in Figure 5 in terms of equivalent stress, computed according to the Von Mises formula:

$$\sigma_0 = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \tag{1}$$

where σ_i stands for the ith principal stress tensor component.

In this case, an average value has been taken between inner and outer layer of the statue. Filtering the maximum value above 10 MPa other gradients may be highlighted in the left arm area and from the thighs up to the hips.

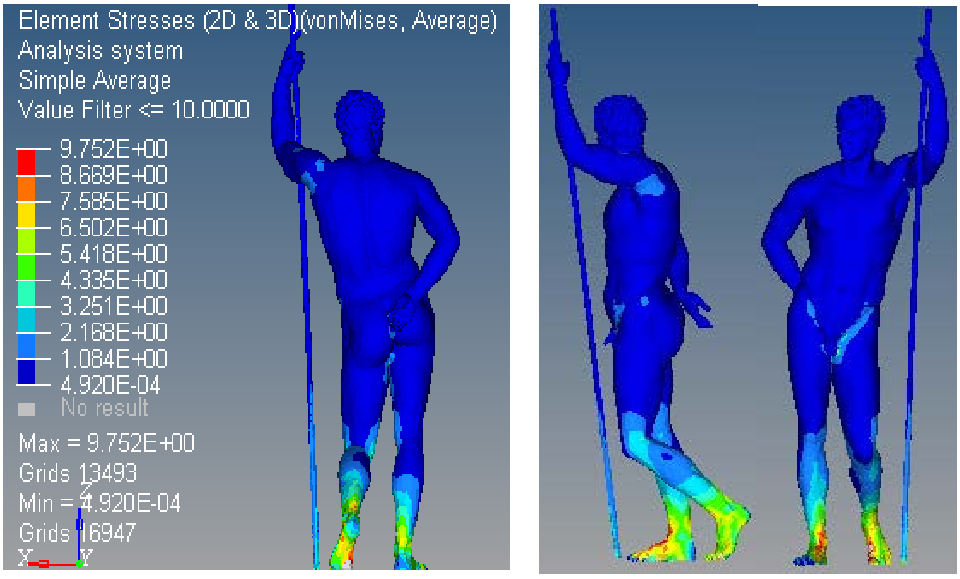
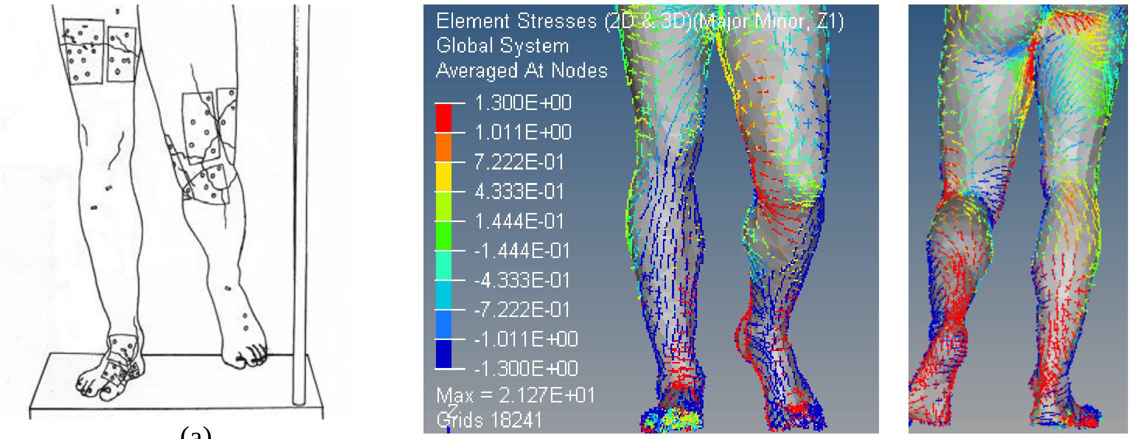


Figure 5 BC#1 with non-uniform thickness distribution: Von Mises equivalent stress (averaged on the layers, units are in MPa)

Although maximum values are far from failure stresses (qualitative value for yield 100-130 MPa), static analysis confirms critical areas where original cracked fragments were located (figure 6.a). In particular, Figure 6.b shows a plot of the principal stress tensor at the legs, to give evidence of the changes in direction and values. At the knees up to the thighs, a transition occurs with both compression and tension. It becomes axial stress at the ankles, in traction in the back and compression in the front according to the BC on the ground and to the displacement that occurs under the load condition.



(a) (b)

Figure 6 (a) qualitative representation of cracked areas and fragments after the first restoration; (b) BC#1 with non-uniform thickness distribution: principal stress tensor with values (units are in MPa)

Assuming the boundary conditions of BC#2, maximum displacements decrease of about 25%. Stress distribution becomes more severe in terms of magnitude and amplitude of the gradients, although they are still lower than failure stress.

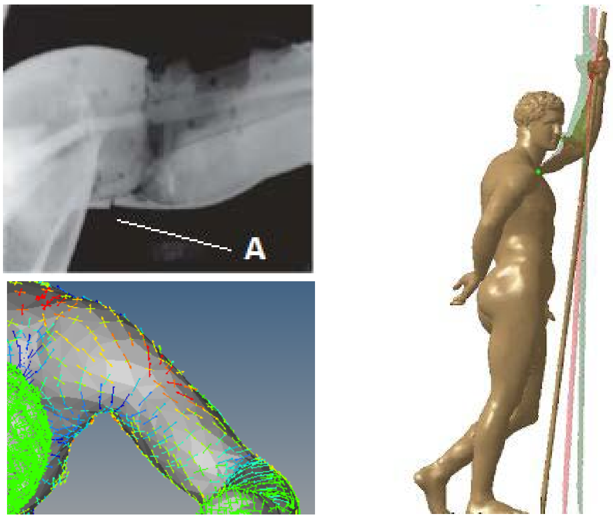
4.2 Modal Analysis and hypothesis of fragment re-alignment

CAE investigations may also help considerations about statue exhibition. In particular, via modal analysis, natural frequencies may be found for preliminary anti-seismic evaluations. Moreover, modal analysis may also give information about deformations under occasional loads like those related to carriage and handling.

In this case, modal analysis gives similar results for each BC and thickness distribution: 5 Hz and 10 Hz for bending forward, like in static deformation, and in its orthogonal direction. Over 20 Hz for transversal bending (ZX plane) and over 25 Hz up to 32 Hz torsion modes.

As shown in Figure 7, the arm was found as a separated fragment with lacuna. Figure 7.a also shows a view from the top of the principal direction of the stress tensor around the left arm. Back part of the shoulder is in tension due to bending, effect that may increase the risk of fracture.

Its reconstruction was made two times: the first one adding a bronze detail (19^{th} century), the second one via reconfigurable inner-support plus resin addition. Photographic evidences show different postures among these interventions, so that, major investigations about possible reconstructions seem necessary. A preliminary result is shown in Figure 7.b. It is obtained using the 3D model to re-align the arm with a translation in the point A of the RX of figure 7, and a rotation made along the axis defined by the feet. This direction has been chosen imagining that the crack has been propagated due to an exasperation of the stress during bending. Figure 7.b shows 2 rotations of 3.5° and 7 ° respectively (the red and the green).



(a) (b)

Figure 7 (a) RX of the left arm and qualitative principal stress distribution; (b) arm rotation, preliminary hypothesis

5. Conclusions

This paper shows some results of CAE investigations on an ancient bronze statue found in Rome. Many restorations have been done to improve material conservation and guarantee structural stability. Although some simplified hypotheses are necessary, the static analysis confirms that fragments are associated to areas with higher stress concentration. They are ankles, thighs and left arm nearby the shoulder. The left arm is also critical for the bending natural mode of vibration, which is related to the first frequency (about 5 Hz). Major simplified hypotheses are related to the thickness distribution and the definition of the constraints. A sensitivity analysis has been made according to: compliance of the constraints at the ground; uniform versus non-uniform thickness distribution. Changing the type of constraints, static deformation increases with the compliance between inner frame and right leg (up to 35% concerning the deformations); lower effects are due to the non-uniform thickness distribution.

Other effects not investigated are: actual values of the material characteristics; role of the discontinuities along the fragments (presence of plates to make the conjunctions).

The low effect due to changes in the thickness distribution is probably related to the adoption of a 3D model of the bronze statue obtained via digitalization. This allows high accuracy in shape, better estimating change of surface curvature and, thus, bronze final area.

Robustness of the results, changing the constraint conditions, and preliminary correlations with the original fractures may encourage the adoption of CAE as analysis method of critical conditions. Moreover, its combination with CAD modeling and digital acquisition may assist fragment reconstruction and posture optimization.

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