Design of the New Inner Frame for the Vittoria Alata di Brescia: How Engineering Design May Support Ancient Bronze Restoration

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Abstract. Mechanical design and engineering can support projects with high-added value in the Cultural Heritage field, such as restoration of artefacts like statues and architectonical decorations. Many examples have been carried out, along the recent past, in the field of ancient bronze restorations (as for Marco Aurelio, Satiro Danzante di Mazara del Vallo and Principe Ellenistico). Engineering design techniques help the assessment of structural problems through physical measurements and FEA simulations; the digital acquisition of the surfaces represents a fundamental base for CAD modelling, and the inner frame design helps for guaranteeing stability and manoeuvrability requirements for transport and exhibition. Workflow peculiarities and requirements to accomplish the restorers' activities and investigations may highlight best practices and rules. The design of the new inner frame of the Vittoria Alata of Brescia, an ancient roman bronze statue, represents a recent example of this kind. Its design workflow was provided in the loop of the restoration program, and it was assessed considering structural integrity, surfaces protection, inner inaccessibility, and dimensions. The solutions adopted are the result of a collaborative process with restorers to evaluate each proposed concept, in compliance with the studies and the constraints highlighted during the investigations. CAD-CAE tools applied starting from the 3D acquisition, helped the development and its verification, reducing the efforts during the manufacturing phase and final set-up. This paper aims to discuss the obtained result demonstrating how structural analysis and mechanical design anchored to 3D acquisitions may help restoration of bronze statues.

Keywords: CAD-CAE, Structural Analysis, Cultural Heritage, Design for Restoration, Vittoria Alata.

1 Introduction

Mechanical design and engineering are increasingly supporting restoration of artefacts like statues, architectonical decorations and paintings. Engineering design techniques may help the assessment of structural problems through physical measurements and Finite Element Analysis (FEA) simulations; the digital acquisition of the surfaces is currently fundamental for CAD modelling, and, often, inner frame design is carried out guaranteeing stability and manoeuvrability requirements for transport and exhibition.

Measurements involve surface corrosion, material composition and integrity, technological information related to fabrications and previous restorations. Major examples of this are provided by relevant projects such as the one made on the Michelangelo’s David [1] or applications for deeper investigations such as the Roman bronze statue of the Pugilatore at Museo Nazionale Romano [2]. Peculiar studies and design activities involve seismic preservation and monitoring, as demonstrated in [3]. Simulations for structural integrity are also increasing their role: besides the architectural field, original applications were carried out to evaluate stability of many statues such as the roman equestrian bronze of Marco Aurelio [4] or the imperial marble statue of Alba-la-Romaine (France) [5]. This work also demonstrates that many different CAD investigations may be provided starting from digital acquisition, such as measurement report and collection [6] and posture restoration. Further works connected to this topic are related to fragment recognition and assembly of potteries [7] or statues [8]. Finally, the applications related to digital design and additive manufacturing to aid transportability and manoeuvring [9], exhibition and lacuna reconstruction [10] deserve to be mentioned.

Fragment alignment is naturally linked to the design of inner frames to guarantee stability. Many ancient statues were found in pieces and the original solutions for their postures and stability is often unknown, in some cases also the final aspect may be under discussion, when lacunas are relevant. Examples of this are provided by the statues of the Satiro Danzante di Mazara del Vallo [11] and la Minerva di Arezzo [12, 13]. In the first case, the final design accomplished the requirements of fragment positioning with regulations through precision screws and spherical joints, and material compatibility through contact surfaces made by compatible resin. In the second case, the favourable accessibility of the inner parts allowed the design of a wireframe able to align the original sherds with the reconstruction of the lacunas that can be removed easily. Other important bronze statues, like Principe Ellenistico [8] and the Vittoria Alata of Brescia present structural peculiarities related to their integrity status and to the restoration made after their finding in the nineteenth century. They are quite continuous along the body, thus there are not easy to be accessed inside. The support devices inside both the statues consisted of frames with square section beams linked to the bronzes by compact concrete fillings and, only in the case of the Principe Ellenistico, bronze plates with rivets. The fillings acted as rigid stiffening between bronzes and basements where the frames were inserted. The filling naturally provided solidity among sherds, original or not, and reduction of local bending loads, but it resulted to be not able to guarantee about surface corrosion. In the last century, this old kind of arrangement was amended by new restoration criteria that prefer showing original fragments by themselves without invasive new reconstructions and diffuse fillings.

In this paper, we are going to report the efforts to design and set-up the new inner frame for the Vittoria Alata di Brescia (Fig. 1) for its new exhibition in the Capitolium of Brescia. It has been done after a restoration programme carried by the Opificio delle Pietre Dure (OPD) of Florence that included the removal of the nineteenth century filling.

The preliminary assessment defined not only the requirements related to the new architectural exhibition, designed by Juan Navarro Baldeweg, but also the structural effects induced in the bronze shell by the filling removal. It was obtained through experimental analysis and FEA simulations as discussed in Section 3 after the presentation of the statue and its restoration project (Section 2). Then, in Section 4, relevant concepts and final development are discussed, so that, in Section 5, main conclusions are outlined.

2 The Vittoria Alata and its New Exhibition Set-Up

The Vittoria Alata of Brescia (Fig. 1), datable around the middle decades of the 1st Century A.D., represents a precious and rare archaeological artefact in bronze, which has fortunately escaped to the common practice of re-use (for further information about the statue's history, the restoration intervention and the new exhibition set-up [14,15]).

Fig. 1. A view of the new exhibition of the Vittoria Alata in Brescia's Capitolium (Courtesy of Foto Studio Rapuzzi Brescia).

The statue's details brought out by the restoration, and the analyses about the used manufacturing technologies, suggest that it was made by a high-level atelier, which could rely on a mature artist for the choice of the model and the harmonious construction of the figure, and on qualified and well-organized workers.

The statue was discovered in 1826, during a campaign of archaeological investigations carried out in the Capitolium of the ancient city of Brescia, where it had been intentionally hidden, in antiquity, with its wings and arms detached and neatly placed near the body. At that time, specialists recognised the female figure as a winged victory (Vittoria Alata) in the pose of writing the name of the victor in battle on a shield, not found in the excavation, which the divinity held on her raised left leg. This interpretation guided the first nineteenth-century restoration aimed at displaying the large bronze statue. To give stability to the entire structure and allow the wings and arms to be attached, an ingenious metallic structure, with joining mechanisms for the originally detached parts, was inserted inside the statue. This supporting structure was held in place by a massive filling, which remained in place until 2018, when, after careful studies and inspections, it was decided to remove this inner system as it was no longer able to safely accomplish the function which it was designed for.

The urgent restoration work has become the hub of a wider process of research, conservation and valorisation [16,17]. The project has been promoted by the Municipality of Brescia and the Fondazione Brescia Musei, with the direct involvement of the Opificio delle Pietre Dure in Florence, the Soprintendenza for Archeologia Belle Arti e Paesaggio for the districts of Bergamo and Brescia, the Lombardy Region, and thanks also to the support of private individuals. It has led to huge progresses in the knowledge of this extraordinary workpiece and its peculiar history. In addition to archaeologists, restorers and scientific experts from the involved institutions, external specialists and technicians from various universities and research institutes contributed to the implementation of this ambitious project in accordance with a modern interdisciplinary research approach.

At the end of the restoration, the Vittoria Alata has been exhibited in the Capitolium of Brescia, in a space specially designed by the Spanish artist and architect Juan Navarro Baldeweg, who was able to enhance the statue with a particularly monumental setting in which intentional references to antiquity can be seen. The statue has been placed in an elevated position on a cylindrical base, inside which is concealed the connection with an anti-seismic platform placed at the floor level. The Botticino marble, used for this supporting cylindrical base, evokes the shafts of the columns, while bricks and mortar cladding of the walls are inspired by Roman architectural materials (Fig. 1).

The Vittoria Alata posed an interesting challenge both for the restoration purposes and for the related studies and research. A thorough examination of the state of preservation and preliminary investigations carried out with the acoustic emission technique, conducted to the decision of emptying the statue of filling and old supporting structure, designing a suitable new support that would allow the various parts of the statue to be safely assembled and positioned high up on the new basement connected to the anti-seismic platform.

The critical areas, initially observed through an examination of the statue, were the conspicuous dimpling of the lower neck, the evidence of the welding point, the consequent stretching of the metal on the back of the neck and the series of cracks running through almost the entire circumference. Moreover, several cracks and missing parts of the upper part of the chiton, at the insertion of the left arm, and the detachment of a portion of the roll of folds of the cloak, were very visible, in addition to some other small breaks distributed. Thermography also revealed a problem of discontinuity in the lower back part of the robe, and radiographic examinations revealed numerous cracks and breaks that were hidden under the layers of bronze alteration products and of previous restorations. The usage of X-rays brought into a sharper focus a large area of possible weakness in the left side of the statue due to both the thinning of the alloy in that area, and to its progressive mineralisation and suffering due to the imperceptible change in posture caused by the natural process of degradation of the organic filling materials that secured the 19th century support to the statue and by the different balance caused by the weight of the wings. This weakness was also made evident by acoustic emission surveys repeated in successive years [18].

At the end of the emptying process, conducted stratigraphically with the criteria of the archaeological micro-excavation [19], a photogrammetric relief of the internal surfaces was made possible, also having the chance of linking it to the 3D relief of the external surfaces, becoming useful as a support and reference system for specific mappings [6]. This system of sequential images made possible the revealing of further points of discontinuity, such as the precariousness of the attachment of the bust in the upper part of the joints to the lower part of the figure, which was therefore reinforced by the assembly and welding of the horizontal folds of the cloak.

All these structural weaknesses were therefore considered, studied and used for the mapping of the critical points, which had to be taken into account for the construction of the new support that would allow the new exposure in full safety.

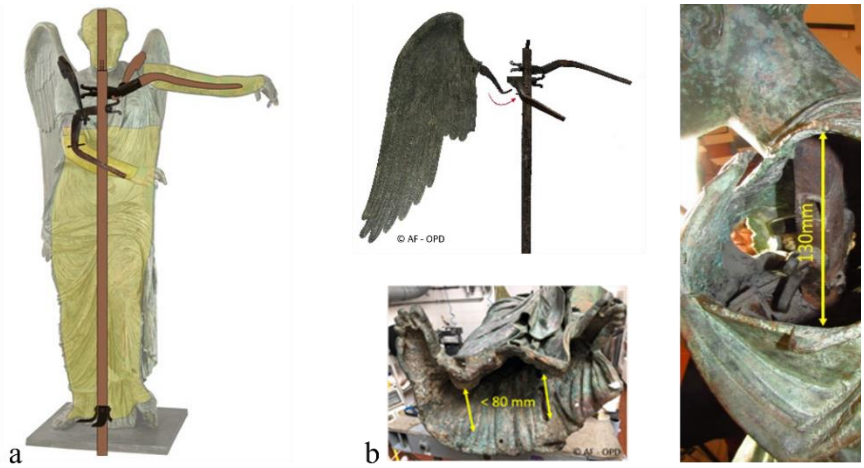

Fig. 2. a) The old frame and the filling (light yellow); b) The old mechanisms for wings and arms connections and the useful openings of the statue.

The 19th-century inner frame, originally designed to support the statue and drowned in the mentioned filling, is presented in Fig. 2. It consisted with a central square-section beam with transverse elements to connect wings and arms in the respect of the central body. Transverse elements were fastened by means of screws and regulated through spacers. Wings were hooked, one for each transverse element. Arms were engaged through pins with rectangular sections. The stability between the inner frame and the bronze shell was guaranteed, as said, through a conglomerate filling, that presented also organic composition, that guaranteed adhesion and solidity between the internal structure and the bronze shell of the statue. It also furnished a structural advantage on the central body, increasing its stiffness. The central beam was inserted in the base of the neck through a prismatic guide embedded in the filler of the head. At the base, a positioning cross ensured the correct place of the central beam, before filling the statue. The central beam supported the load entirely, as confirmed by the slight and discontinuous imprint of the bottom perimeter on the basement put in place in the 1950s. No specific regulation for the relative positioning of arms and wings were defined except the use of shims.

3 Design Requirements, Analyses and Concept Design

From the previous sections, it can be deduced how the new frame design could be challenging and the high number of different requirements to be accomplished. Main functionality of the new inner frame is withstanding the weight of the central body, wings and arms, respectively of about 217 kg, 30 kg (left wing), 38 kg (right wing), 12 kg (left arm), 8 kg (right arm), allowing the connection to the new anti-seismic base provided by THC and a height from the floor of 1.6 meters as requested by the museal set-up. Moreover, material integrity of the ancient bronze must be prevented without overload at critical points defined by diagnostics, as reported in Section 2. The set-up must be able to be disassembled and it must be made of materials compatible at the bronze interface, to guarantee surfaces. Assembly must accomplish the feasibility of manoeuvring the statue both in OPD and Capitolium, allowing final regulations on site. Other relevant constraint is the limited room for assembly manoeuvre inside the statue. Access towards the inside of the statue is possible only from the base, from the arms openings and on the shoulders where areas for wings insertion are provided (Fig. 2b).

From the structural point of view the final map of critical areas, derived by visual inspections and diagnostics like radiography and eddy current, highlighted the necessity of: 1) not providing support by the base of the statue; 2) preserving the weak area of the left hip; 3) preventing new opening of the neck crack.

The filling removal represented an additional element of weakness since its presence increased the overall stiffness of the central body, avoiding relative rotations. To define a reference structural state for the evaluation of the new inner frame concept, FEA was adopted.

3.1 Preliminary structural evaluation by FEA

FEA model was based on the 3D acquisition made by a structured light device by Mattia Mercante [20]. For facilitating the computation, the initial high-density cloud has been filtered to achieve a suitable coarse triangular mesh. Loads have been distributed as gravity loads after an experimental evaluation of thickness distribution and of the central body centre of mass. The thickness measurements have been made by Eng. Giorgio

D'Ercoli (ISCR, Roma), through calliper in all the accessible areas of the statue (Fig. 3a) and the measurement of the centre of mass position has been achieved by the Apice Srl using dynamometers and winches in one of the operations of movement during the restoration.

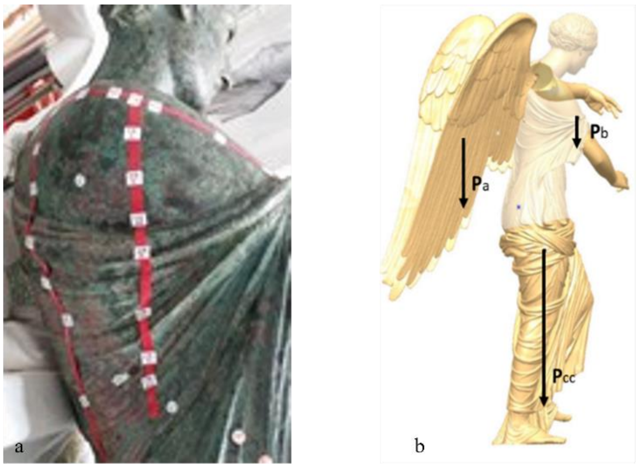

Fig. 3. a) experimental point distribution for thickness measurements on the upper part; b) Simplified load distribution

Crossing these results with the 3D model of the external surface of the central body of the statue and its weight, two distributions of thickness emerged, one for the torso, with a rather uniform trend, on average about 6 mm, and a more variegated one of about 8 mm in average, in correspondence of the legs. In Fig. 3b, it is reported a side view of the loads diagram to the resulting centres of mass for the arms (P_b), the wings (P_a) and the central body (P_{cc}). The reference structural state has been defined as the one achieved simulating the presence of filling, reproducing the condition of the statue before the restoration intervention. The action of filling has been simulated as a lock of relative rotations. The wings have been applied in contact with the statue assuming a rotation of the connection hooks. Their critical effect on the left hip area has been detected as a stress state related to a bending moment induced by the wings, that in the ancient restoration may touch the back of the statue (Fig. 4). The final maximum displacement on the head has been assumed as a sizing criteria for the new inner frame, so that, the stiffness effect of the filling may be reproduced in accordance to stress distribution at the neck and the left hip, not greater than the reference case.

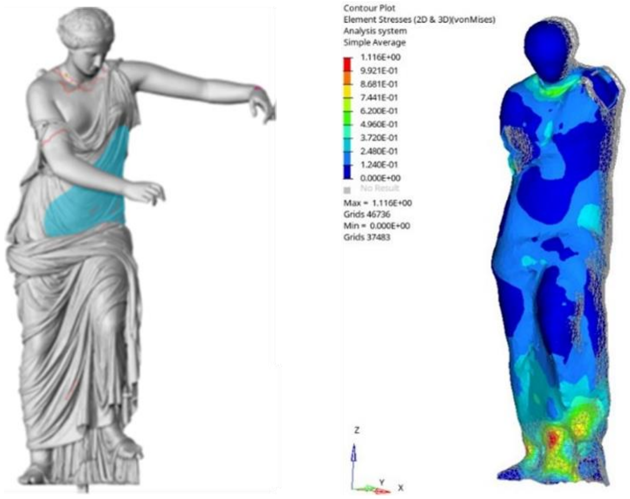

Fig. 4. Left: critical area map (in blue, results of the Eddy Current test about material weakness; in red, cracks); right: preliminary FEA displacement results (mm), in grey undeformed shape.

3.2 Digital Mock-up of the Concept

The internal surface of the statue was not completely available, due to inaccessibility, and, above all, it was not a simple offset of the outer, being more like an irregular pipe with a very rough finishing without evidence of the external folds of the drapery. According to this, the contact surfaces with the inner frame have been derived by offset and smoothing operations from the outer one, guided by the knowledge of the thickness measures and the visual inspection of the surfaces. The functional components of the concept are load support interfaces and stabilization interfaces to limit the oscillations of the bronze with respect to the support, regulations of the interfaces in the respect of problems of alignment with the supposed contact surfaces and in the respect of contrast tension. The contact surfaces of the support interfaces were identified in the left thigh and in the right shoulder (Fig. 5).


a b c

Fig. 5. Preliminary layout of the contact interfaces: a) right shoulder; b) left leg; c) stabilization at the breast.

The stabilization interfaces have been set in two cross sections at the height of the breast and at the lower base. In each section there are 3 horizontal pads adjustable in translation by screws. The section at the height of the breasts also provides for angular adjustment in correspondence with the spherical graft of the struts in the three discs placed at approximately 120°, at the height of the right breast, of the lower left armpit hollow and on the right back. The structure is completed with a contrast support at the height of the thigh.

To limit, as possible, the final deflection of the head, for the central beam, an H section was opted. It is oriented to intercept the original graft left in the head, by using an oriented pin. The graft was defined with gap condition to avoid overstressing the neck. Correct orientation of the central beam is defined by the stabilization interfaces at the base, assigned to specific positions not critical for the mineralization of the area. Regulation of the interface positions in the respect of the contact of internal surfaces of the statue is guaranteed by spherical joints of the struts in the metallic anima of the interfaces. Regulation of the loads by screws positioned at the base since the struts of the thigh and the shoulder are positioned along the core of the H beam, or directly near by the interfaces for the stabilization ones. The wings are engaged from the upper openings by means of prismatic shanks that are housed in special crosspieces connected to the central beam. For the support of the arms a pantograph arrangement has been selected so that proper tension can be regulated to guarantee stabilization.

Regarding the materials, it was decided to make the internal structures in stainless steel with contact interfaces in compatible resin (PE 664 hardener IPE 764 (100: 50)). The realization of the pads has been examined since the concept phase, due to the obstacles related to the positions to be reached; the need to guarantee reversibility and stability of position during forming; the necessity of moving the statue from laying down to stand up.

Fig. 6. a) Resin bronze-frame interfaces; b) particular of the back of the left leg interface.

To reduce position errors, a direct molding process has been defined. It works after covering the resin with a film suitable to avoid leaks. Markers positioned on the internal surface have been adopted as fastening elements of the pads during the forming phase, as well as the repetition of multiple tests, have ensured good precision of execution and repeatability of positioning. Fig. 6 shows right shoulder, left leg and stabilization interfaces with part of the steel supports.

During the restoration, diagnostics and inspections confirmed that the central body consists with 2 parts joined by weldment along the bottom of the hip. Weldment integrity has some weakness, so that in the absence of supports at the base of the drapery, we opted for the insertion of steel cables (Fig. 7) capable of linking the lower part of the garment, which was connected to the rest of the body with internal welding, currently not entirely safe. The positions of the three cables are at different heights to avoid interference with internal surface of the bronze.

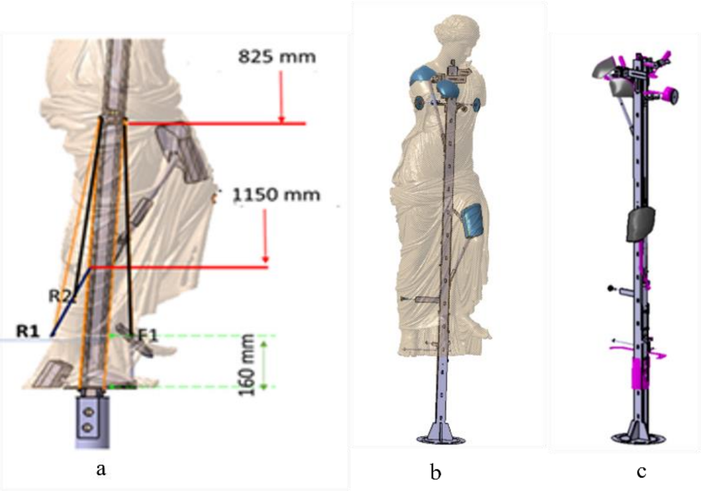

Fig. 7. a) Cables set-up for safety of the shell at the bottom; b) Mock-up as built; c) Alignment between “as built” and final design (in purple).

4 Preliminary and Final Set-Up

Preliminary set-up was made at OPD to test the solutions developed from the concept design. This was made maintaining the statue laying down, horizontally. Testing included: verification of the manoeuvring of the central beam and its insertion in the guide of the neck; marking the areas of the contact interfaces and verifying the room for assembly. Thanks to markers, breast, shoulder and thigh interfaces have been placed prior to assembly struts and central beam. Fig. 7b shows the "as built" model provided by Capoferri. Fig. 7c reports the alignment of the initial interface design with the “as built” model. The alignment of the two projects was done by bringing to coincidence (by minimizing the relative distances) the three points of comparison of the lower position of the central pole on the statue and, subsequently, by rotating the planes of the statue-interface contact at the points related to armpit and breast, until they coincide. The differences between the two central poles are of a few millimetres and, despite some differences in the positions of the thigh strut, it can be concluded that the two models comply with a good approximation. Finally, in Fig. 8, the gap among the statue and the basement is shown to demonstrate that accomplish of the request about preservation of the bottom part.

Fig. 8. Detail of the final set-up to show the suspension of the statue.

5 Conclusions

The restoration of the new exhibition set-up for the Vittoria Alata of Brescia included the design and set-up of a new inner frame suitable to support its parts (central body, arms and wings) and preserve material integrity. The openings for manoeuvring and the wide lengths represented the major obstacles to define feasible solution. CAD-CAE analysis starting from 3D digitalization of the outer surfaces were the starting point of the work to assess the structural integrity and to evaluate assembly drawbacks. Concepts were defined considering these drawbacks and, after digital mock-ups, physical prototypes were built to assess possible limits and tolerances of interface manufacturing and mounting. Co-operation with restorers and integration among simulation and practical set-up optimized the scheduling and decision making, demonstrating how mechanical integrated product-process design may help restoration in the cultural heritage field.

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