Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Reconstructive Hypothesis of the Historical Aviary in Prince Doria Palace, Genoa (Italy)

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ABSTRACT: The structural and technological reconstruction of the large aviary in Prince Doria Palace (Genoa, North-western Italy) is proposed, taking into account its historical and cultural context. The study is characterized by strong multi-disciplinary approach, in which data derived from different analyses (historical, archaeological, structural and numerical) are directed towards the synthesis framework: it is comprehensive not only of the reconstructive hypothesis of dimensions and shape, but also of the technological issues implied in the building of this architectural work. The numerical simulations play a fundamental role in achieving the final goal: several analyses (Finite Element Method) are carried out, aiming to verify the feasibility of the various reconstructive hypotheses (considering the constructive techniques and the craftsmanship in the 17th century). The numerical models are analysed (taking into account various loading conditions) and the most realistic one, from the static point of view, is selected.

1 INTRODUCTION

Ancient constructions are strongly characterized by their history. In fact, time effects and modification on such kind of structures are various and significant, in terms of:

- damage derived from historical events of rare severity (earthquake or wind);
- structural alterations or dead-load variations, caused by static interventions or changes in the use designation of the building;
- long-term decay of mechanical characteristics of materials.

Usually, the study of the behaviour of historical masonry structures, considering their building phases, is finalized to the safety-factor evaluation related to the collapse (Calderini and Lagomarsino 2005, Calderini et al. 2006).

In this research, on the contrary, the structural analysis is directly aimed to the individuation of the most feasible architectonic shape of a particular steel structure (the large aviary in Prince Doria Palace, Genoa - Italy), that does not exist anymore.

At the beginning of the 17th century, Giovanni Andrea Doria, Genoese noble, decided to build this structure in the garden of one of the most significant palaces (Fig. 1) in the architectural environment of Genoa (thriving maritime township in the north-western Mediterranean Sea in the 13th century, Oligarchic Republic in the 16th and 17th century).

In particular, the interest in this aviary, that unfortunately did not survive up to the present day, arises from its exceptionality and originality, due essentially to the large dimensions and, consequently, to the complexity of the constructive techniques necessarily used in building.

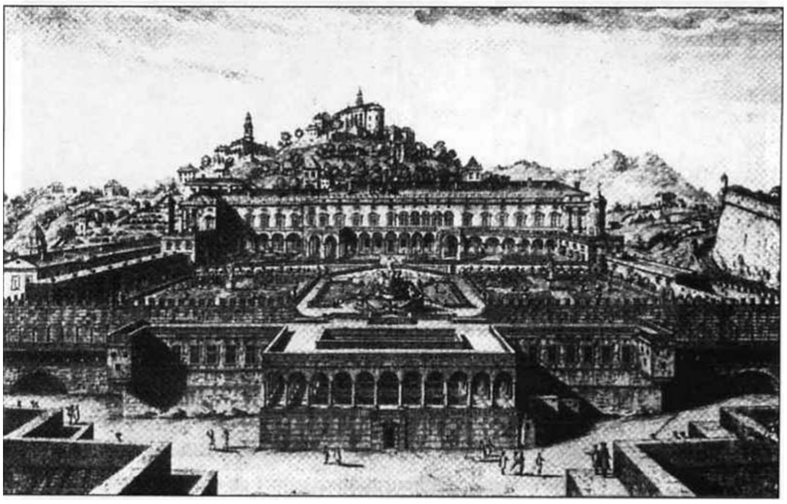


Figure 1 : View of Prince Doria Palace (A. Giolfi, G. Riviera, G.L. Guidotti, *Veduta del Palazzo del principe Doria*, 1769).

2 THE VOLARIES IN THE ITALIAN RENAISSANCE AND 16TH - 17TH CENTURIES

In Genoese area, between 16th and 17th centuries, the garden space was going to have an important role in the aristocrats' villas.

The Genoese nobles considered the garden as a private space, besides being expression of power and wealth. In the garden, comforts and pleasures had to be present. This aspect was noted and appreciated by several foreign travellers, visiting Italian cities.

In Genoese villas, architectonical elements of naturalistic inspiration, as ponds, grottoes and volaries, were often present. The volaries, used to fence exotic or local birds in, were not built following precise constructive rules. Boyceau de la Barauderie asserted: *"… the aviaries have to variously enrich the gardens, thanks to their different shapes and building features and thanks to the numerous kinds of birds, collected for their voices and singing"*. A unique and consistent dissertation about the volary shapes is not feasible to develop, but classes having analogies in functions and symbolic meanings can be identified (Camurati 2001):

- volaries with complex and elaborated structure, inspired by Varone's aviary in Cassino; they have celebrative architectonic value and they are autonomous elements in the garden;
- small volaries, generally built of masonry, roofed by elegant steel coverings;
- wide volaries, that include the natural elements in the garden, more than be sided to these. Trees and shrubs may be present inside, with the aim of enclosing the wood in a big cage.

The great aviary of Prince Doria Palace seems to lie within the last category.

3 THE AVIARY OF PRINCE DORIA PALACE: RECONSTRUCTIVE PROCEDURE

The aviary of Prince Doria Palace, although being one of the numerous wonders contained in the villa, was the historical structure which had better represented the grandeur of the garden for almost a century: because of its peculiarity in dimensions, shape and design techniques, the aviary was considered unique and spectacular at European level.

These are the main reasons of interest in the study about the reconstructive hypotheses of this exceptional structure. But, in literature, the information about the Genoese *volaries* was not complete and they were considered as particular elements of a more general topic (the architecture of landscape and gardens). So, it is necessary to expand the research under the historical point of view, in order to identify the cultural background in which the original aviary was inserted.

The basic data are deduced from the archaeological excavations (carried out during the restoration of the Prince Doria Palace, 1998-2001) and from the stratigraphical analysis on the border wall, that partly allowed the filling of the informational gap about the structure (Musso 1995, Mannoni 1997, Biagini 1999).

Moreover, performing numerical analyses on the hypothesized structural models is very important in the final identification of the most realistic structural hypothesis.

So, as previously stated, the following study has to be characterized by an effective multidisciplinary approach, in which data derived from different analyses (historical, archaeological, structural and numerical) are directed towards the synthesis framework.

One of the main problems to face is the lack of design graphical documents or detailed images. So, the importance of correlating data from different sources and crossing distinct information arises.

3.1 *Documentation analysis*

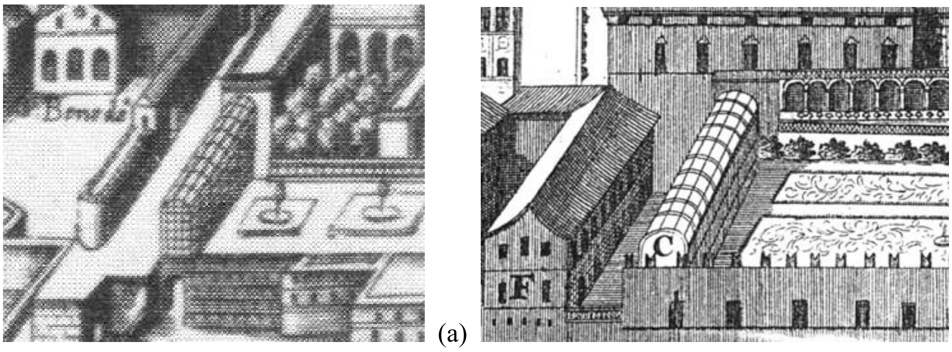
The first phase of this research deals with finding the literary sources and archive documents, both iconographic and descriptive. In particular, the State Archive in Genoa and the Doria Pamphilj Archive in Rome were consulted.

3.1.1 *Iconographic sources*

The historical images often do not provide objective representations of the real depicted situation.

The mere impossibility of doing precise drawings and the need of re-elaborate the sketches often lead to contradictory data. So, the critical review of these sometimes misleading images is necessary.

In 1637, A. Baratta depicted the aviary long and high, having parallelepiped shape, rectangular in plan, with a round barrel vault as in Fig. 2a. In about 1655, an anonymous painter (Collezione Topografica del Comune di Genova, inv. no. 1945, Genoa) drew the same area of the garden, without any important difference: the aviary height seems to be less than the terrace one.



(a) (b)

Figure 2 : Detail of: (a) *La Famosissima e nobilissima città di Genova con le sue nuove fortificazioni,* A. Baratta (1637) in Poleggi (1976); (b) Woulkanmer, 1708-1714, in H.J. Dixon*, Garden and grove*, 1996.

In the 17th century, G. Costanzo, painted a view of Genoa harbour, including the facing buildings, in order to produce a planimetric and bathymetric representation. The oil painting technique can not provide for sharp details, but a lighter green spot in the area where the volary should have been built let us think that a tower toppled by a cupola, with trees inside could have been present (Fig. 3a). The aviary seems to be sided to the wall, but the presence of buttresses can not be excluded.

The view by Woulkanmer (Fig. 2b) was published in 1708, when the aviary seems to have been yet demolished. But the depicted situation may refer to a previous age. In this drawing, similar to the ones of Baratta and Costanzo, the aviary studs and arches are represented by two sided lines: this sign may means that two coupled structural elements were present.

In 1796, G.B. Brusco described the garden area where the volary was built in a planimetric view (Fig. 3b): couples of points (even not regularly spaced) which may represent the vertical supporting elements of the structure are drawn. The plan shape, deduced by this image, is trapezoidal.

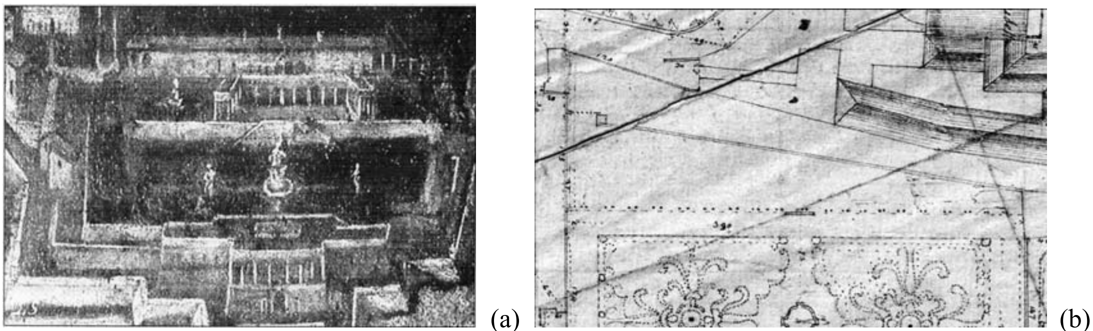


Figure 3 : Detail of: (a) *Rilievo planimetrico e batimetrico del porto di Genova*, G. Costanzo, 17th century (Sea and navigation Museum, Genoa); (b) *Rilievo planimetrico del giardino di Palazzo Doria*, G.B. Brusco, 1976 (Liguria Regional Board of the Ministry for Monuments, Genoa).

3.1.2 Historical archive sources

The research in the State Archive in Genoa and in the Doria Pamphilj Archive in Rome leads us to find interesting documents (Camurati 2001).

The Act (dated 4th April, 1602), through which Battista Orsolino was commissioned by Giovanni Andrea Doria to realize the design of the aviary in the sea-front garden, is one of these documents. From the written words, it can be achieved that the designer was given of complete freedom in the constructive choices; on the other hand, the structure had to be built within April, 1603.

In 1624, *"various craftsmen and material"* were requested: this need may be derived from a significant restoration or maintenance intervention. From 1682, in other documents, the selling of the steel obtained by the volary (perhaps partial) demolition was cited. It can not be excluded that static problems developed and the need of volume reduction arose (some foundation blocks for the poles, showing anomalous failure, were found during the excavations).

3.1.3 Traveller reports

At that time, Genoa was the departure city for the Italian tour of several (mainly German and English) travellers. From their descriptions, written in travel reports, interesting information may be obtained.

J. Furttenbach (*Newes itinerarium italiane* …, 1627, in Magnani 1997) proposed a detailed, and so rather feasible, description of the aviary: it was steel made, huge in dimensions (106 steps in length, 10 in width, 20 in height, 1 step=0.8 m), but he never cited the trapezoidal shape. He wrote about *"a tower with a cupola"* in the central part of the aviary that stood over 15 steps. Other reports suggested that the volary dimensions were surprising, even because of the description of the inner trees (Evelyn 1644, Morfot 1658), and they cited the central cupola (Evelyn 1644, Merli-Belgrano 1874). All the writers agree with the use of steel in building the aviary.

3.2 Data from the archaeological survey

The archaeological campaigns interested various zones in the garden of Prince Doria Palace. They were executed by the Institute of History of Material Culture, with the supervision of Dr. M. Biagini (1999, 2000 and 2001).

The excavations were mainly performed to point out the successive phases in the garden history and to achieve information about the hydraulic devices, but they also obtained interesting data about the aviary. For a detailed description the reader may refer to the original documentation (Biagini 1999).

The excavations permitted the firm individuation of some of the main dimensions of the aviary. The archaeological analysis, discovering the calcareous base-blocks inserted in the aviary foundation wall, confirmed that the structure was made of studs, which the holes in the blocks were used for (Fig. 4).

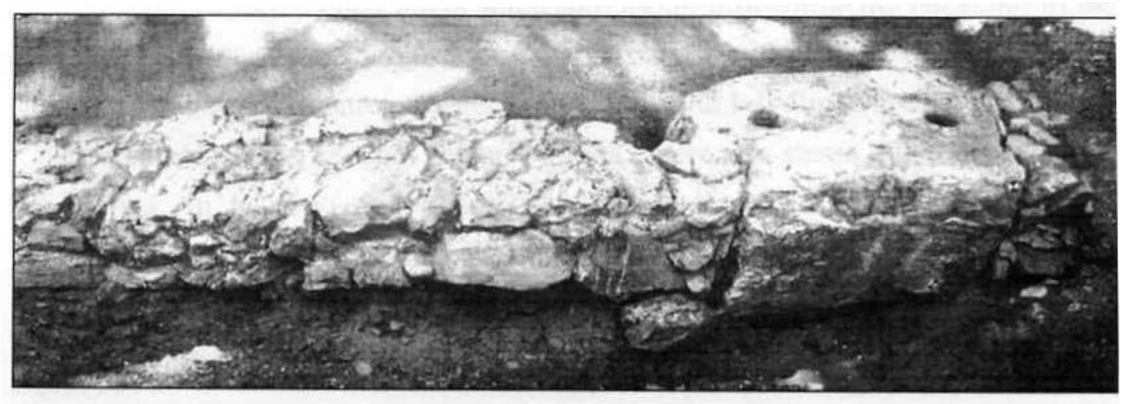


Figure 4 : Side view of the foundation wall with the stone base-block for the studs.

The planimetric location of the coupled studs (which represented a part of the structural main frame) was precisely determined on eastern and southern sides. The oxidation traces inside the holes for the studs confirm that they are steel made. The stratigraphical analysis of the base-blocks allows the evaluation of the pole diameter. Moreover, different stud typologies were found. In fact, in the eastern and southern sides, the studs, inserted in cylindrical holes, were supported by steel plates. In the northern part of the foundation wall, the supports were made of lime mortar and filled with marble rubble and soil. These supports prevented the stud displacements, but did not eliminate rotations. To this aim, steel elements (cables) were disposed; they came out from the supports (filled with lead) of the inner bases.

In the western side, the archaeological analysis did not highlighted direct traces of the structural constrains. However, one-to-one correlation between the buttresses and the stone base-blocks was noticed. Even if nowadays many buttresses are not the original ones, the wall stratigraphical analysis picked out that the new counterforts have been re-built in the same location of the ancient ones. The estimated age of construction of the original buttresses, which is before the end of 16th century, makes clear that the structure was built on the basis of the existing counterforts.

Moreover, the relevant bulging phenomena of the border wall toward the inner garden have to be underlined. According to the chronological reconstruction, based on the available data, during the volary building, the wall had bulging deformation (some centimetres) toward the garden and this led to the original buttresses construction. Taking into account that the wall was not built in a homogeneous way, the thrusts transmitted to it by the aviary structure may determine evident deformations that probably caused, after the volary clearance, the inevitable demolition of the original buttresses, in order to re-build them.

Moreover, the archaeological research highlighted interesting features about the presence of the central tower. The inner base-blocks in the central area have holes of larger diameter than the others; so the idea is the different structural function of these base-blocks. The presence of other inner bases can not be excluded.

4 RECONSTRUCTIVE SCHEME: EVIDENCES AND UNSOLVED MATTERS FROM THE ANALYSIS OF HISTORICAL AND ARCHAEOLOGICAL DATA

For its impressiveness and peculiarity, the aviary strongly characterized the garden and it was too large and magnificent not to be noted. For these reasons, during the design phase, particular care was taken to the element proportion study, in order to ensure the harmony of the whole structure.

On the basis of the previous information, the volary could have been built with trapezoidal plan, covered by a long barrel vault.

From the archaeological excavations, the length of the eastern (83.2 m) and northern wall (8 m) was determined. Once verified that the western side (82.6 m) of the aviary was on the current location of the border wall, the length of the southern side could be evaluated (14.5 m). Furttenbach, the German traveller, provided the correct dimensions in plan and also described the height of the structure and the central tower. But these measures are very different from the iconographic suggestions: in fact, he indicated that the structure was 20 steps (about 16 m) high and the central tower was 15 steps (about 12 m) high in addition.

The main topics in order to understand the aviary are related to the rising structures, in particular to the total height of the volary. As previously cited, the only indication about this refers to the iconographic sources and to the Furttenbach's description.

On the basis of the iconography, the ridge of the barrel vault that cover the aviary was less high that the quote of the Palace terrace (Fig. 2). The univocal determination of this measure is not possible: nevertheless, taking into account that nowadays the terrace is 10 m high from the garden quote, the volary height (at the ridge of the barrel vault) may be hypothesized in 7-9 m.

The main steel frame seems to be made of coupled studs and transversal arches. The frames are regularly spaced (4 m) and the pole diameter is about 0.07 m. On the eastern and southern side, the studs were inserted in cylindrical holes. In the northern part of the foundation wall, the supports prevented the stud displacements, but did not eliminate rotations. So, additional steel elements (cables) had this structural aim, also stiffening the structure (Fig. 5a). Moreover, on the western side, the way in which the original counterforts were disposed could not be significant if direct correlation with the volary studs is not accounted for.

The archaeological analyses excluded the presence of base-blocks or other kind of supports next to the border wall: so, it can be achieved that the volary vertical elements had to supported by the counterforts, sided to the wall.

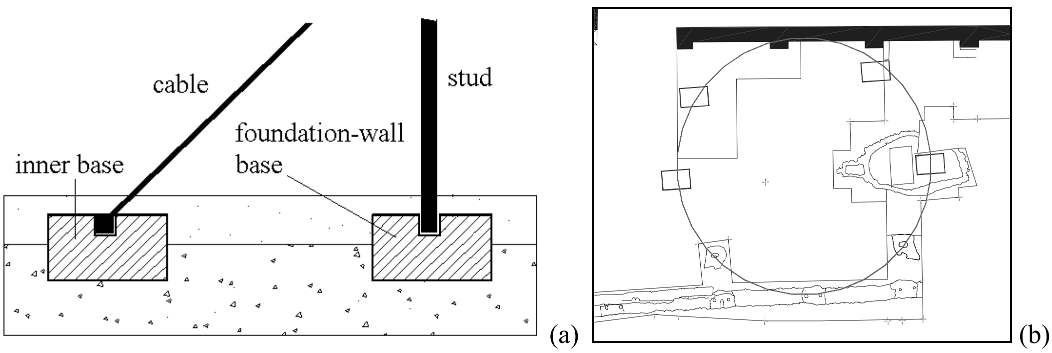


Figure 5 : (a) Support in the northern side of the structure; (b) Possible position of the central tower. In grey, the hypothesized inner bases.

Being impossible to objectively understand the secondary frame conception, in the proposed models, the structural scheme was realized through steel coupling elements (in Italian "calalastrelli") between the each couple of studs and transversal arches and through longitudinal elements connecting the vertical structure. The distance between these elements is 1.6 m along the studs (they are differently spaced along the arches – less than 1.5 m). As described in the following, the structural analysis highlights the need for cable insertion at the arch springing and bracing placing in correspondence of the longitudinal elements.

One of the most complex and interesting themes, in which the exceptionality of the aviary arises, is the connection between the different structural elements.

Using the past building techniques for steel constructions, the manufacturing of the stud as a one-piece element (having the height suggested by the iconography) was impossible. In the specific case of the aviary, the arches as well had to be built in two circular parts, welded together and to the studs. In the structural model definition, the joints between the large-dimension elements are schematized as they were welded; for the other joints, it was supposed they were riveted.

Another topic, not totally clarified by the previously described analyses, deals with the shape of the barrel vault covering the aviary: being a structure with trapezoidal plan, the barrel vault can not have a semicircular shape of constant radius. So, the analysed model of the vault is characterized by a sequence of semicircular arches of different radius, being the ridge line horizontal.

Moreover, the unsolved question of the presence of the central tower may be faced using the structural simulation. The travellers' reports clearly cited it, as in the iconographic sources, it can be figured out only in one case. In Fig. 5b, the possible location of the central tower, deduced by the archaeological study, is described. In the images, mainly derived from treaties about gardens, the most recurrent shape for this element typology is a central tower, with circular or octagonal plan, covered by a cupola.

The hypothesis of construction and subsequent demolition or collapse of the central tower is the most feasible. Considering the complexity and the novelty of this structure for its significant dimensions, the existence of not perfectly studied or realized elements (which could have weakened the structure that the clearance became necessary or the failure occurred) can not be excluded.

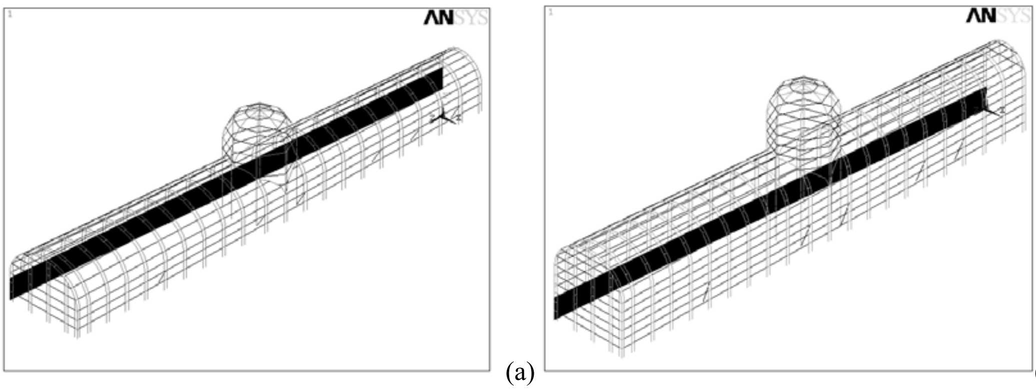
5 NUMERICAL ANALYSIS AND RESULTS SYNTHESIS

Thanks to the archaeological, iconographical and historical studies, a lot of data about the volary structure was found, but some questions are still unsolved. In particular, the height of the volary, the barrel vault shape, the secondary frame conception and the presence of the central tower (cited by Furttenbach) are uncertain.

With the aim of clarify some of these themes, in order to complete the information framework about the volary, several structural analyses, involving two different basic models and introducing modifications in them, are carried out. The numerical simulations are performed using the multipurpose FEM code *Ansys release 5.5*.

Model A (Fig. 6a) is characterized by the height derived by the iconographic sources (9 m); it has a central tower, 6 m in height (less than Furttenbach's indications). This model is also d without considering the central element, covered only by the barrel vault.

Model B (Fig. 6b) is realized on the basis of Furttenbach's suggestions about the height of the barrel vault and cupola.



(a) (b)

Figure 6 : Numerical simulation models: (a) Model A; (b) Model B.

The main frame is made up of coupled studs and semicircular arches; the secondary longitudinal frame (beam elements) is derived on the basis of the element spacing. The presence of coupled studs and arches leads to model a coupling system (schematizing steel elements with rectangular section) put at different distance (1.66 m along the eastern studs, 1.33 m along the western studs, variable spacing along the arches). Using the same spacing, longitudinal beam elements (with rectangular section) are added.

At a possible height, the cables (link elements), connecting the inner base-blocks and the coupling system ("calastrelli") are inserted. The western border wall is modelled as shell elements (0.5 m in thickness, 4 m in height).

In the central tower, with octagonal plan and covered by a cupola, vertical studs and arches of the same dimensions as the previously described ones are used; they are linked in the horizontal direction through beam elements.

Some modifications are introduced in the two basic models: tie-rod insertion in the arches and bracings.

The elastic parameters for steel are deduced by experimental tests on material coeval with the aviary, collected in previous studies (Young modulus E = 1.3 N/m^2).

The structural constraints given by the palace are schematized as translational and rotational ones. The base constraints of the studs are only translational (hinges). In fact, on the basis of the data obtained through the archaeological research, the width of the holes in which the studs are positioned (without any binder) is not sufficient to avoid the rotation.

The linear analyses are performed using different loading conditions: dead load and wind load are assigned to the structure. The numerical simulations provide interesting results about the more probable structure of the aviary, highlighting the need of elements useful for the global static safety.

5.1 Dead load analysis

On the basis of the study about Model A, the static behaviour of the main frame (studs and arches) can be understood: in fact, the analysis of the stress and strain state in the coupled studs and the global deformed shape under dead load are of particular interest.

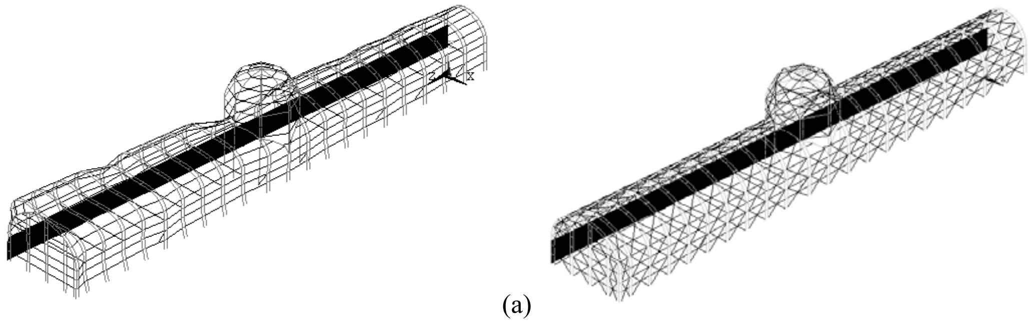
Very large displacements in the coupled studs and arches, if only connected by longitudinal beams, are pointed out (maximum displacement = 0.53 m).

Moreover, the positive effect of the cables in contrasting the arch bulging toward the east side and the poor efficiency of the longitudinal connecting elements are noticed.

For this reason, tie-rod elements are inserted at the arch springing point, with the aim of reducing the significant arch thrust (Model A2). In this condition, the model shows strongly decreased displacements (maximum vertical displacement = -0.06 m; maximum horizontal displacement = 0.07 m), but global deformability is still remarkable (Fig. 7a).

In fact, the lack of longitudinal connection (if only longitudinal beam elements are present) is still an unsolved issue: the longitudinal beams are not able to transmit the stiffening effect of the tie rods in the arches from one frame to the adjacent one. The same for the positive effect of the stiffening structure in the southern side and of the constraints due to the palace.

In order to avoid this problem, other linking elements are inserted (bracings – St. Andrew crosses) between two adjacent transversal frames, corresponding to the longitudinal beams (Model A3).



(a) (b)

Figure 7 : (a) Deformed shape for the dead load in Model A2; (b) Model A4.

In this way, both the vertical and the transversal displacements decrease further (maximum vertical displacement = -0.04 m; maximum horizontal displacement = 0.03 m). The global deformed shape highlights that in southern part, the arches (of largest radius) have relevant displacement in the horizontal transversal direction.

The comparison between the displacement data of the southern and northern parts underlines that the arch span plays an important role for the static safety. In Model A4 (Fig. 7b), having less bracings in eastern and western sides and additional St. Andrew crosses in the southern side, the displacements seem to be reduced (maximum vertical displacement = -0.02 m; maximum horizontal displacement = 0.01 m).

The analysis results point out that no relevant stresses may be found in the structural elements. Therefore, it can be concluded that the global deformability problems are related to geometrical (e.g., studs and arches slenderness) and technological (e.g., steel characteristics) issues more than to extreme dead loads. Young modulus value assigned to steel may be perhaps too low: a more detailed analysis could be needed.

5.2 Wind load analysis

The structural analysis on Model A4, taking into account the wind load, highlights that the equilibrium state of the aviary is very precarious. Modelling the wind actions as medium intensity horizontal pressure (E-W direction, wind velocity V=20 m/s), remarkable displacements are detected (maximum vertical displacement = 0.03 m; maximum horizontal displacement = 0.16 m).

The secondary frame with bracings seems to well distribute the forces among all the structural elements, but, in order to further stiffen the inner structure, other oblique bracings are needed, especially in the steel elements of the eastern and western fronts. In the performed analyses, higher tensile stress values are determined (maximum stress=74.8 N/mm^2); this stress state may compromise the effectiveness of the coupling system and of the element joints.

Moreover, considering one transversal frame, the wind action induces tension in one coupled stud system and compression in the other; this condition varies with the positive or negative sign of wind load. This aspect, due to the transversal thrusts in the model, has a particular meaning if we account for the constraint typology of the stud supports: in fact, the archaeological study determined that these supports are effective in case of compression, but not of tension. This phenomenon could have induced anomalous forces (and, consequently, displacements) in the structure and, in a long time, it could have decreased the strength.

The absence of the central tower (Model A5) do not significantly modifies the structural behaviour in case of wind load; in fact, as in the previously described model, the structure shows relevant displacements in the arches, even if slightly lower than before. On the other side, the wall transversal displacements are strongly decreased (2 times).

The static behaviour of Model B (made on the basis of Furttenbach's suggestions about the height of the barrel vault and cupola) is studied.

The analyses for dead loads do not show relevant structural displacements. If wind load is considered, the global deformation is significant. Very large displacements are noticed in the whole structure, not only the central part, near the tower (maximum vertical displacement = 0.04 m; maximum horizontal displacement = 0.45 m). These values surely lead to static problems.

5.3 Results synthesis

The performed analyses highlighted the care and technological knowledge necessary to build the large aviary in Prince Doria Palace in Genoa, both in the design and in the construction phases. Although some static problems could have been present, the volary lasted for almost one century.

Even if only idealized numerical models could be evaluated, the analyses pointed out interesting data about the elements of the volary structure.

The simulations using the two basic models (Model A and Model B) highlighted that, in case of dead load, the global deformation and stress state in the structure are acceptable for the static safety. Larger displacements are instead noticed for the wind action.

FEM analyses underlined that Model A3, A4 and A5 (for which the height is derived by the iconographic sources) do not show excessive displacements (the higher value is reached for wind load). Despite the poor and not detailed data about the secondary frame elements, the stiffening effect of tie-rod in the arches, bracings and oblique bracings could have permitted to build the aviary, even in the 17th century.

The investigation about the stress and strain states in the structure was a noteworthy topic; in fact, it played a critical role in the determination of the most probable reconstructive hypothesis. Thanks to the FEM analyses, Model B (on the basis of Furttenbach's suggestions) seems to be clearly not reasonable, because of the excessive height.

Moreover, the study confirmed the information from the *in situ* findings. In fact, the stud diameter (determined by the archaeological research) turn out to be sufficient for the structural safety, if accompanied by a particular stiffening secondary frame.

Finally, accounting for different load conditions, it was deduced that particularly severe tensile stresses could have developed in the cables; this state could have led to failure the inner supports in the stone base-blocks (filled with lead).

6 CONCLUSIONS

This paper aims to provide a multi-disciplinary approach, in order to face the issues related to the formulation of reconstructive hypothesis in case of monuments, emphasizing the importance of synthesis and comparison of data from different sources, in order to obtain a more detailed and more realistic overview of the problem.

Combining the elements from the *in situ* findings and from the historical and iconographic studies, some hypotheses on the structural model, related in the most suitable way to the original conception of the aviary, were determined.

The contribution of numerical simulations played a fundamental role in achieving the final goal: several analyses (Finite Element Method) were carried out, aiming to verify the feasibility of the various reconstructive hypotheses (taking into consideration the constructive techniques and the craftsmanship in the 17^{th} century). The numerical models were analysed (considering various loading conditions) and the most realistic one, from the static point of view, was selected.

In particular, the study provides some original contributions in the decision-making processes, in which the selection of the final reconstructive hypothesis about the aviary is made on the basis of structural analyses: the numerical-simulation results allow us to reject the models not able to ensure a life of nearly one hundred years to the aviary and they enable the most proper choice.

ACKNOWLEDGEMENTS

The authors would like to thank arch. Michele Camurati, Prof. Stefano Musso, Prof. Lauro Magnani and Prof. Tiziano Mannoni (University of Genoa).

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