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Strengthening of a wooden covering built in the 18th century

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ABSTRACT: The National Archaeological Museum of Naples is placed in a building founded in 1582. Its most representative part is constituted by a Big Hall having a volume of about 20,000 m^3 and a roof with three superimposed wooden covering orders, which was rebuilt in 1735. Structural damages were caused by several earthquakes, atmospheric agents and material degradation, so that the substitution of the roofing structure with a new one was proposed for more than one hundred years. The author of this paper designed and directed the retrofit interventions in order to preserve the existing structures, having high historical and monumental value. Brief historical information as well as the executed retrofitting structures are described in detail.

1 HISTORICAL OUTLINE

In 1582 the Viceroy of Naples Don Pedro Giron commissioned the arch. Giovan Vincenzo Casale to built a new chivalry barrack. After about 30 years, the viceroy Don Pedro Fernandez de Castro appointed the arch. Giulio Cesare Fontana to transform and complete the building, in order to obtain a university head office. A Big Hall, having dimensions of 23 × 50 m in plan and volume of about 20,000 m^3, was designed as library and was placed at the first floor of the building.

The original wooden roof was damaged by the 1688 earthquake and rebuilt up as per order of the King of Naples Charles III of Spain. The appointment was given to the arch. Giovan Antonio Medrano in 1735, which designed a new covering structure (the current one) composed by two independent orders of wooden trusses, placed at different levels, and a flat vault.

In 1737 the Big Hall was damaged by another earthquake and in 1777 the building was changed in National Archaeological Museum by the arch. Ferdinando Fuga, which was been appointed by the King Ferdinando IV of Spain. Further damages of the roof were caused by the 1805 earthquake and copious water infiltrations. In Figure 1 the entire Museum can be observed, as represented in a print of 1845: the Big Hall of the library is located in the central part of the building.

Several projects based on complete substitution of the roofing structure were proposed between 1894 and 1899, but fortunately they were not realized because of lack of funds. Between 1904 and 1911, some damaged wooden beams were substituted and the vault was suspended to both the orders of trusses to limit its deformations. Further structural damages of the building were caused by the 1930 earthquake.

Figure 1. Archaeological Museum of Naples in 1845.

About the restoration of the Archaeological Museum, the Italian Ministry of Public Works commissioned the author of this paper to assess the roofing structure and design the complete substitution or retrofit of the existing wooden covering. After long and deepen investigations at both historical and structural levels, the author excluded demolition of the building for its high monumental value and proposed the retrofit interventions described below.

In Figure 2 the first floor plan of the building is showed: the Big Hall is placed in the middle. A longitudinal section of the Big Hall with the roofing structure is showed in Figure 3.

2 STRUCTURAL LAYOUT OF THE ANCIENT COVERING

As described above, the covering is composed by (1) an upper roof, (2) a lower roof and (3) a flat vault; the

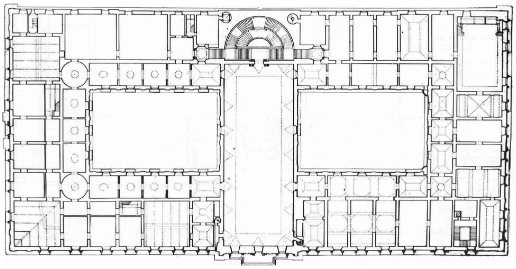

Figure 2. First floor plan of the building.

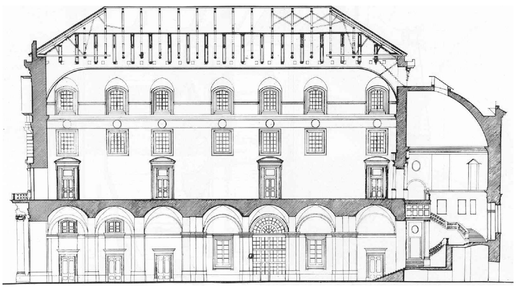

Figure 3. Longitudinal section of the Big Hall.

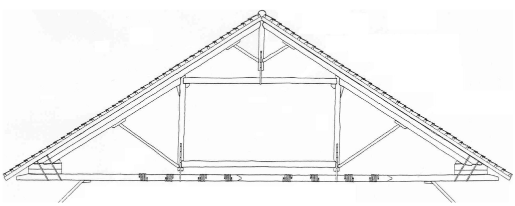

Figure 4. Typical upper roof truss.

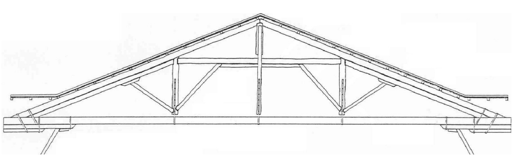

Figure 5. Typical lower roof truss.

two roofing orders are formed by chestnut wooden elements and nailed connections. The upper roof is constituted by Palladian trusses, which are composed by two 33° inclined-pitch struts and a tie beam with span of about 23.10 m (Fig. 4).

The impost height of the lower roof is smaller than the one of the upper roof and the pitches are inclined of 22° on the horizontal direction (Fig. 5).

The third roofing order is constituted by a flat vault. This last one is composed by a lattice of poplar wooden ribs having cross-sectional area of 12 × 20 cm and centre-to-centre distance of 45 cm. The ribs are

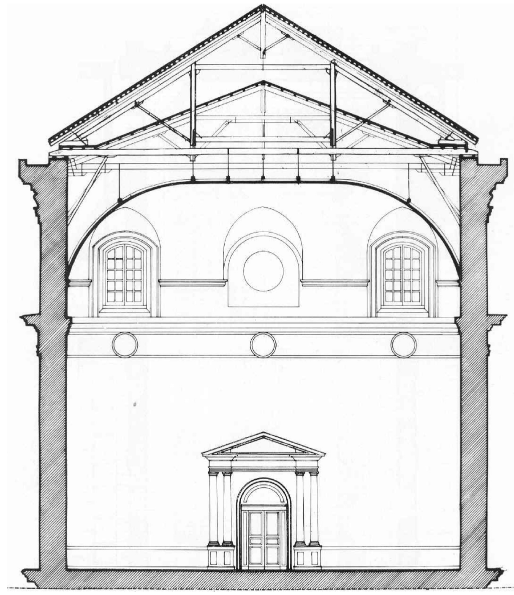

Figure 6. Transverse section of the Big Hall.

connected themselves by distributing fillets having cross-sectional area of 10 × 5 cm. The ceiling of the vault has thickness of 6 cm and was supported by the ribs lattice through iron wires. The three covering orders were designed to accomplish different functions. The upper roof, having four pitches, is the real covering and had to protect the underlying works by atmospheric events. The pitches inclination of about 33° allowed smaller axial forces in truss elements and minimized the wind effects. The intermediate roof has an impost height smaller of about 80 cm with respect to the overlying one and staggered trusses. The pitches, having an inclination of about 22°, supported a lapilli protecting layer to avoid that possible water infiltrations from the upper roof can reach the vault. The structural function of the second roof was to carry the wooden flat vault, that was in turn the ceiling of the Big Hall: fillers and fresco paintings of high value were realized on its intrados. The three covering orders can be observed in the transverse section of Figure 6.

3 FAILURE DIAGNOSIS

Detailed survey of all wooden covering elements allowed to determine the structure geometry and the failures listed below:

- large deformations were observed on the vault with relevant depression of its flat part;
- the connections of the chestnut trunks that constitute the tie beams underwent slips up to 11 cm in the lower trusses and 24 cm in the upper trusses;

Figure 7. Flat vault suspended to the trusses.

– almost all tie rods, which connected the vault to the tie beams of the upper trusses, were highly stretched to advantage of the ones (almost all released) that connected the vault to the tie beams of the lower trusses;
– the most part of trusses joints had inadequate connections;
– more bars were highly deflected (tie beams and struts), twisted or disjoined;
– the most part of the trusses had lack of planarity;
– local deformations were observed on the lower covering flush coat;
– compression cracking of masonry was localized near the truss supports;
– some wooden elements were locally rotten or subjected to biological attacks;
– some tie beams and struts were cracked;
– wide water infiltrations were concentred in small zones of the covering.

A zone of the flat vault suspended to the lower trusses can be observed in Figure 7.

4 STRUCTURAL ANALYSIS

In order to evaluate the stress state of the existing structure, upper and lower trusses were modelled through one-dimensional finite elements, assuming a planar model with constraints that simulate the actual behaviour of the existing structure, based on the on-site surveys. The flat vault was modelled as box vault constrained by hinges placed on the perimeter masonry walls. Several load patterns were considered to simulate the actual actions applied to the structure and to carry out the failure diagnosis. For this scope, an inverse analysis was performed to obtain the load condition that provoked the surveyed failures, as made by everyone that must determine the causes of a failure.

In general, it can be stated that a part of surveyed failures depended on the oldness of the structure or construction defects, while other failures were expected to be caused by correlated events (i.e., construction phases, earthquakes, repair interventions executed in the past). The wood degradation phenomena were caused by attacks of xylophages insects and meteoric water infiltrations due to bad waterproofing or failure of the covering tiles. Compression cracking of masonry that occurred near the truss supports was due to insufficient material strength with respect to the applied loads. The disjointed connections of the trusses, that were spread across the entire structure, were principally caused by their bad project and execution. The connections were deficient for (1) number and diameter of nails, (2) deformation of connecting plates, (3) plasticization of holes, (4) oxidation of metallic elements. In most cases the connections did not transfer the internal forces from a bar to another one, resulting in disjoined bars. Design and construction errors determined lack of planarity for many trusses. Their realization using more chestnut wooden trunks connected themselves and lack of both vertical and horizontal bracings provoked high vulnerability with regard to horizontal displacements.

Several structural analyses were carried out to determine the causes of the serious deformations undergone by most part of the structure. A first cause is related to the different construction phases of the Museum. The original configuration of the building, which was started in 1585 and completed in 1615, consisted of a two-storey central part comprising the Big Hall and a unique one-storey lateral hall (the western one). Large structural asymmetry and different free height of the perimeter masonry piers of the Big Hall were at the origin of the serious failures provoked by the 1688 earthquake, after which the original covering was demolished. Owing to this asymmetry, also the 1737 earthquake caused severe damages to the structure. Structural analyses confirmed that the slips between the trunks of the tie beams were induced by the relative horizontal displacements occurred during seismic vibrations of different masonry piers supporting the trusses. Applying to the structural model (composed by lower truss and vault) a relative displacement between external constraints equal to the medium elongation of the tie beams, flexural deformations of the tie beam (and then the ones of the suspended vault too) equal to about 20 times greater than the normal service ones and axial forces in the bars were obtained by the analysis. Therefore, also these results showed the disjoined bars.

Only in 1742, the first floor of the eastern annex of the building were built, making symmetric the structure of the Big Hall. Construction of the second floor of both western and eastern annexes, completed in 1793, increased lateral confinement of the vertical structures of the Big Hall and reduced the absolute displacements at the top of the masonry walls, resulting in a building similar to the one of Figure 1.

Another cause of failure is the structural repair intervention executed between 1904 and 1991 by the Italian Department of Public Works. In order to substitute some wooden beams of the lower trusses, some of these ones and a part of the vault were suspended to the upper trusses. At the end of the intervention the vault was suspended to the substituted elements again, but suspensions became active only after larger deformations, that required the laying of further tie rods. The intervention consisted of the following phases:

– suspension of the vault to the tie beam of the upper trusses, by means of new tie rods;
– substitution of chestnut trunks that constituted the tie beams of the lower trusses with new squared wooden beams and metallic connections;
– connection of the vault to the new tie beams through metallic tie rods;
– removal of tie rods (that allowed the temporary suspension of the vault to the tie beams of the upper trusses).

After these operations, the vault experienced further depressions due to elastic deformation of the new structures, so that its connection to the upper trusses was necessary. Therefore, these interventions provoked further deformations of the flat vault and damages of the upper trusses, which were not designed to support the self-weight of the vault.

5 INTERVENTION PHILOSOPHY

The choice of the intervention type required a deepen study and a long work, because of the historical-monumental importance of the building and its structural complexity. In order to avoid demolition and reconstruction of the structure, the author studied appropriate methodologies to execute non invasive interventions, according to the international criteria for restoration of monumental buildings and to the static conditions of the existing structures. After long and deepen reflections, it was decided that the intervention had to meet two fundamental principles:

– to ensure safety of people and archaeological treasures;
– to preserve the existing structures.

Firstly, it was believed necessary that the three covering orders must satisfy the structural safety, so their functions and static behaviour have been modified, eliminating every mutual interaction. Then, the three covering orders are statically independent each other and the following functions were defined: (1) the upper roof must protect the underlying structures by the atmospheric agents; (2) the lower roof is the second protection for fresco paintings; (3) the flat vault is the ceiling of the Big Hall and supports fillers and paintings. According to this project choices, new structures

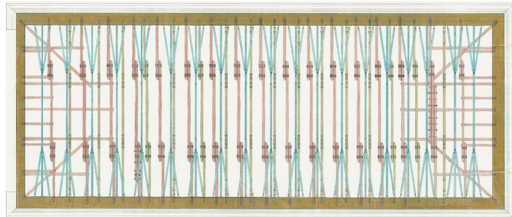

Figure 8. Plan of trusses and prostheses.

supporting the vault were studied. In fact, the pitched coverings can be strengthened to support both dead and live loads acting on them, while the flat vault was not able even to sustain itself, given the large span of the Big Hall. Therefore, new prostheses were added to the covering structure to support the vault, satisfying at the same time the following primary requirements:

– appropriate resistance (to support the vault self-weight);
– appropriate stiffness (to limit deformations and to avoid damages to fresco paintings and fillers);
– possibility to be assembled into smaller spaces, without removal or damage the existing wooden structures;
– reversibility of the intervention, that is the possibility to dismantle the prostheses in the future.

The hypothesis of new (steel, laminated wooden or prestressed concrete) trusses was removed, because they would have radically modified the aspect of the present covering and would have required demolition of all pitches. The hypothesis of a tensile structure was put aside too, either for lack of reliability of anchorages or for incompatibility between deformations of the cables and maximum displacements tolerable by the vault and its frescos. After long study, the solution was to realize steel prostheses composed by three-span statically determinate Gerber beams, whose number is equal to the one of trusses and that were placed between these last ones. In Figure 8 the roof plan is represented and it is possible to see the relative position of metallic prostheses with respect to the one of the trusses.

Every prosthesis is composed by two lateral spans and a middle one. The lateral spans are constituted by a spatial system made up of two inclined box-section struts (Ø159 mm/4) and one horizontal beam (two European sections UPN 240). The middle span is composed by two coupled sections UPN 240. The boundary systems of the prosthesis to the existing masonry structures were realized by means of coupled $150 \times 100 \times 12$ mm angles. The end restraint of the beams were designed with particular attention (especially with reference to the spatial ones). The three covering orders (upper truss, lower truss and flat

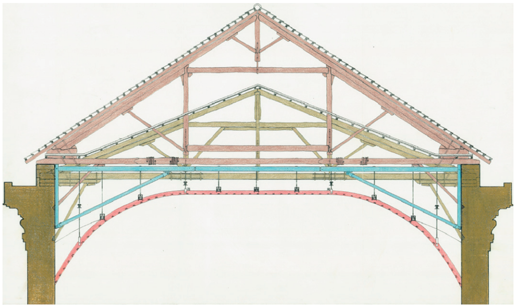

Figure 9. Typical transverse section of the covering.

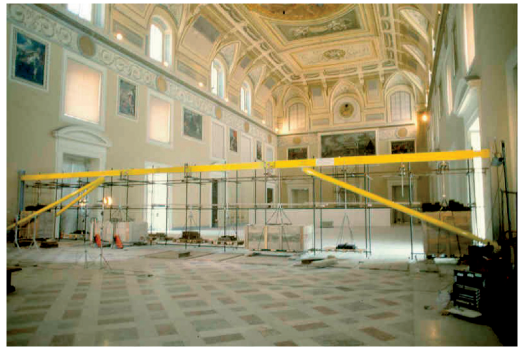

Figure 10. View of the Big Hall and prosthesis prototype.

vault), as well as the metallic prostheses, are showed in Figure 9.

Because of the bad conditions of masonry, especially near supports of the upper trusses, the project foresaw the retrofit of the upper zone of the masonry, in which the boundary systems had to be anchored. The strengthening of masonry was realized with 80 cm-long Ø22 perforations, reinforced with Ø8 inox steel bars and injected with mix of water and cement at the pressure of 1.5 atm. In addition, a Reinforced Concrete (RC) strip was realized on the top of masonry walls, in order to connect them and to support the upper trusses. This strip, anchored in the underlying masonry, was executed by parts of length equal to the centre-to-centre distance of the trusses, suspending every truss to the two adjacent ones for the time that was necessary to execute the phases of work.

Figure 11. End spans of two prostheses.

6 WORKS EXECUTION

The first phase of work, as described above, consisted of realization of the RC strip on the top of the masonries to connect the walls themselves and to give effective support to the upper trusses. Successively, the masonry was strengthened in the belt along which new steel structures would have been applied. In order to assess the analysis results, a prototype of prosthesis was assembled in the Big Hall and was loaded, according to the project documents. The Big Hall, whose coverings had to be retrofitted, and the prototype are showed in Figure 10.

After the assessment on the effectiveness of the designed structures and of the boundary layout, the assembly of every prosthesis between the flat vault and the lower trusses started, as per the executive phases listed below:

1. Laying of 150 × 100 × 12 mm angles to support the end cantilever beams, by means of metallic plates anchored to the masonry; every boundary system was composed by two coupled vertical angles of 150 × 100 × 12 mm and one inverted T-shaped of 150 × 100 × 12 mm.
2. Assemblage of the two Ø159 mm/4 inclined box struts to the boundary system placed in the horizontal angles of 150 × 100 × 12 mm.
3. Assemblage of the horizontal beam (composed by two coupled sections UPN 240) on the boundary system placed in the two vertical angles of 150 × 100 × 12 mm.
4. Connection of the two inclined struts to the horizontal beam through spatial constraint.
   End spans of two prostheses just assembled on site are showed in Figure 11.
5. Laying of the middle beam between the lateral spans.

After that the prostheses were assembled, a new suspending system of the vault was realized. This one was constituted by threaded Ø12 steel tie rods, whose upper end was connected to the horizontal beams of the prostheses while the lower one was joined to the wooden ribs of the vault, by means of U-shaped metallic plates obtained by 100 × 5 mm straps. After assembly of all vault suspensions (operating on top end

Figure 12. Prosthesis with vault suspensions.

bolts of the threaded bars) it was possible to lift the wooden vault until to obtain their original geometry. The entire operation was conducted by monitoring the whole structure, in order to lift it without damages of both bearing elements and ceiling frescos. One of the realized prostheses, as well as the vault suspensions, is showed in Figure 12.

The last stage of the retrofit was structural restoration of the wooden beams that constituted the trusses of the upper roof and lower one.

7 CONCLUSIONS

The historical reconstruction of the events that characterized realization and life of the wooden covering structure of the National Archaeological Museum of Naples and the inverse structural analyses performed on it, allowed to determine the causes of the surveyed failures. The choice to preserve structures of great historical and monumental importance required deepen investigations, with the purpose of define a correct intervention therapy. The design choices of the author looked to ensure the safety of both people and archaeological treasures, as well as the preservation of the whole existing covering.

In order to avoid massive interventions and tampering of the existing wooden structures, it was chosen to obtain three statically independent covering orders. Both upper and lower wooden trusses were restored, while the support functions of the flat vault were entrusted to spatial metallic prostheses. These ones allowed to get back the considerable deflection of the structure. Before interventions on the covering were executed, the tuff masonry walls of the Big Hall were restored in the upper zone.

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