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Complex Covering Timber Structures in Monumental Buildings: a Study Case

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Abstract The paper deals with the study of the ancient timber structures of the Royal Palace of Naples. The attention is focused on the complex covering of the Guard Room (XXIX) of the Historical Apartment. Firstly, geometrical and mechanical *in situ* surveys are presented. Then, the capacity of the structure in terms of deformation and resistance is evaluated through numerical analyses on purposely set up 3D FEM models.

Keywords: Ancient timber structure, ceiling vault, *in situ* survey, structural analysis

Introduction

The analysis of ancient timber structures shows some difficulties related to several factors, like the high features variability due to the material nature, the inaccessibility to carry out in depth surveys, the insufficient information about the used past technologies. Nevertheless, during time timber elements are often exposed to biological degradations, closely connected to the environmental conditions, and to failure anomalies, such as splitting, shakes, cracking. Therefore, the static behaviour of a whole structure, should be identified after an accurate *in situ* evaluation of the state of conservation of single members and their complete characterization. Preliminary diagnostic inspections are needed to evidence any damage and decay situations, to find and eliminate their causes and, at the same time, to characterize the structure as respect to the mechanical properties, for determining the actual load-bearing performance and capability.

In this paper, after an overview of the ancient timber structures of the Royal Palace of Naples (Mazzolani et al. 2004, Mazzolani et al. 2006, Mazzolani et al. 2009), which are an evidence of the past ability of workmanship in timber carpentry applications and techniques, the attention is focused on a case study, which is the complex covering structure of the Guard Room (XXIX) of the Historical Apartment (Grippa 2010). For the purpose of acquiring a comprehensive knowledge of the systems, the analysis methodology has been developed through the following steps: 1) geometrical survey, aiming at the identification of the structural scheme by means of *in situ* inspections; 2) failure diagnosis and visual grading, aiming at the evaluation of material defects and deterioration degrees, and then of the mechanical properties of old timber elements; 3) structural modeling, aiming at the definition of geometrical, mechanical and loading models, corresponding to different phases of the structure life; 4) numerical analysis, for the evaluation of the structure capability in terms of strength and deformation, carried out according to Eurocode 5.

The Timber Structures of the Royal Palace of Naples

The Royal Palace of Naples is located in the historical centre of the town. The square body which encircles the Honour Court was built between 1600 and 1613; it corresponds to the original design by the architect Domenico Fontana (1543-1607). The extension works were carried out between 1700 and 1800. The building has been Royal Palace from 1600 to 1946; actually it houses the Museum of the Historical Apartment, the National Library and the Superintendence to architectural heritage offices (Fig. 1a, b).

The Palace is articulated on three main levels with vertical structures made of tuff masonry walls and horizontal ones composed by either beam floors and vaulted ceilings or tuff masonry vaults (Fig.

1c). The roof structures are realized by trusses and tiles. All the trusses were originally made of timber, but some of them, due to the weather degradation occurred during time, have been recently substituted by either reinforced concrete, steel or glued laminated timber trusses. At the 3rd level there are horizontal timber beam floors; between the 3rd and 2nd floors there are generally false ceilings, realized by both vault and in plane grids partially suspended to the floor above; at the 2nd level both masonry barrel vaults and timber structures are realized (Fig. 1d). In particular, almost the timber systems cover the halls of the Historical Apartment, which is located at the first floor of the noble part of the building, around the Honour Court.

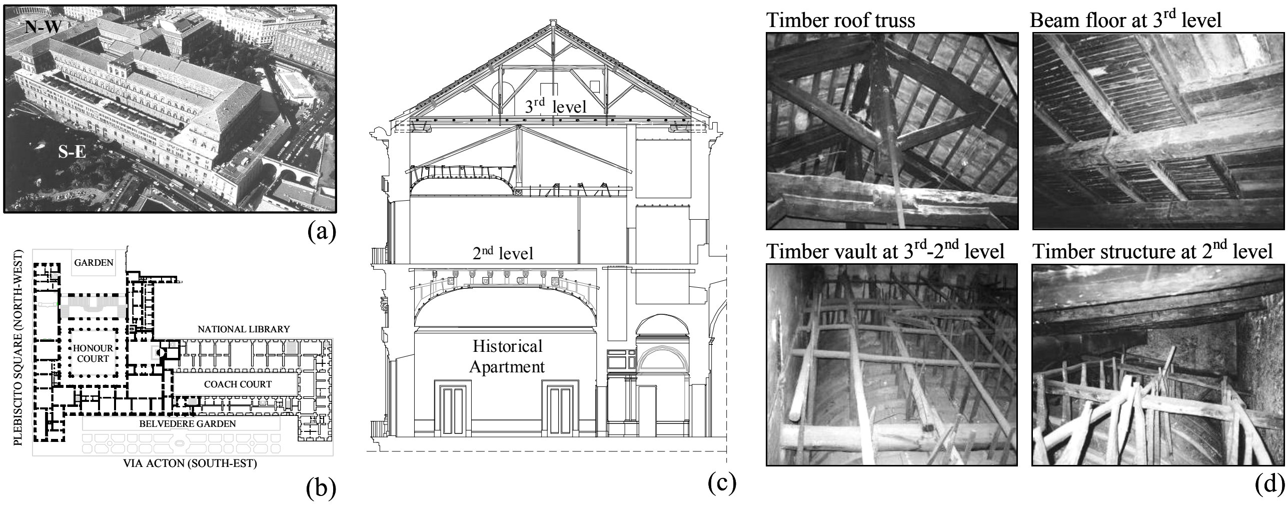


Figure 1: The Royal Palace of Naples: (a) Global view; (b) First floor plan; (c) Typical structural section; (d) Typical timber structures

These complex structural systems, datable between the XVII and the XVIII centuries, were generally realized by means of a composition of two different sub-structures, such as the beam floor, whose function is to bear vertical loads, and the light vault or vaulted ceiling, as the supporting skeleton of the reed laths, lined at the intrados with a coat of lime and plaster, as the base of the stucco. Wherever the spans between the perimeter masonry walls are small, the false ceilings were erected as self-bearing vaults. For large spans, the vaults were connected and partially suspended to the upper floor structures by means of wooden links. After all, during the survey, three different structural types have been detected (Fig. 2): 1) the self-bearing vault, it leaning on the perimeter masonry walls only; 2) the vault linked to the beam floor above; 3) the vault linked to an ad-hoc supporting structure independent from the floor. Peculiar case is the roofing structure of the Guard Room (XXIX), which is the object of this paper.

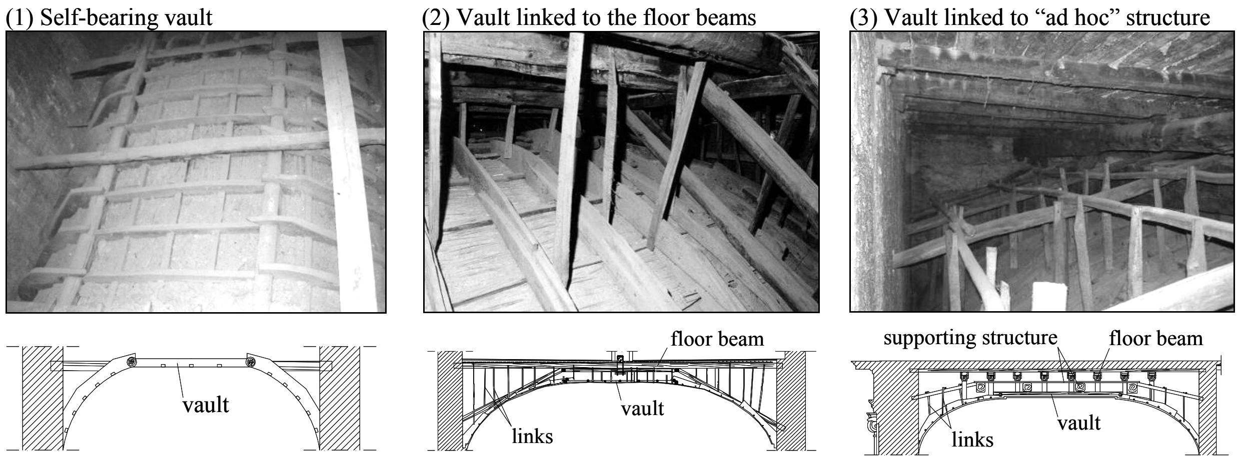


Figure 2: The Historical Apartment: types of the covering timber structures

The Complex Covering Timber Structure of the Guard Room (XXIX)

Geometrical Survey The complex covering structure of the Guard Room (XXIX) is composed by two main superimposed units, connected each other: the vaulted ceiling and the vault supporting structure. They are datable in the second half of the XX century.

Vaulted Ceiling It covers a large surface, 12.50×16.60 m^2 sized. It has a reversal boat keel shape, with a central skylight at the vault crown. The timber skeleton is realized by means of ribs and splines (Fig. 3a, b). The rib curvature is conferred by connecting aligned elements, upright arranged and having 5×20 cm^2 size, by metal plates and iron nails. The ribs are connected by means of wooden links to the upper floor structure along the major span of the floor and to the purposely erected supporting beams along the minor span of the floor. Regular grids of splines elements jointed each other are fitted between two contiguous ribs, having rectangular cross-section, 6×4 cm^2 sized.

At the vault crown perimeter 4 circular elements, 10 cm diameter, are linked to the upper tie trusses beams and to the stiffening frames by means of timber elements, 3×6 cm^2. They are also connected to the upper r.c. roofing structure through 12 metallic ties, 3 for each side, 30 mm diameter (Fig. 3a, b). The completion of the vault is realized by metallic net, within a layer of plaster cast, as a typical construction practice of the XX century for the vaulted ceilings.

The skylight is located at the vault crown and covers a rectangular surface, 7.70×3.90 m^2 sized (Fig. 3a, b). The structure is realized by 4 timber beams with rectangular cross-section 15×20 cm^2, nailed to the adjacent vault crown perimeter elements. They are suspended to both the trusses ties and them stiffening frames elements by means of wooden links. A double frame of reticular metallic beams are connected to the perimeter ones. Eight metallic plates support the transparent sheet of the skylight. The chain of the lamp is suspended to the glass-concrete skylight of the above r.c. roofing structure.

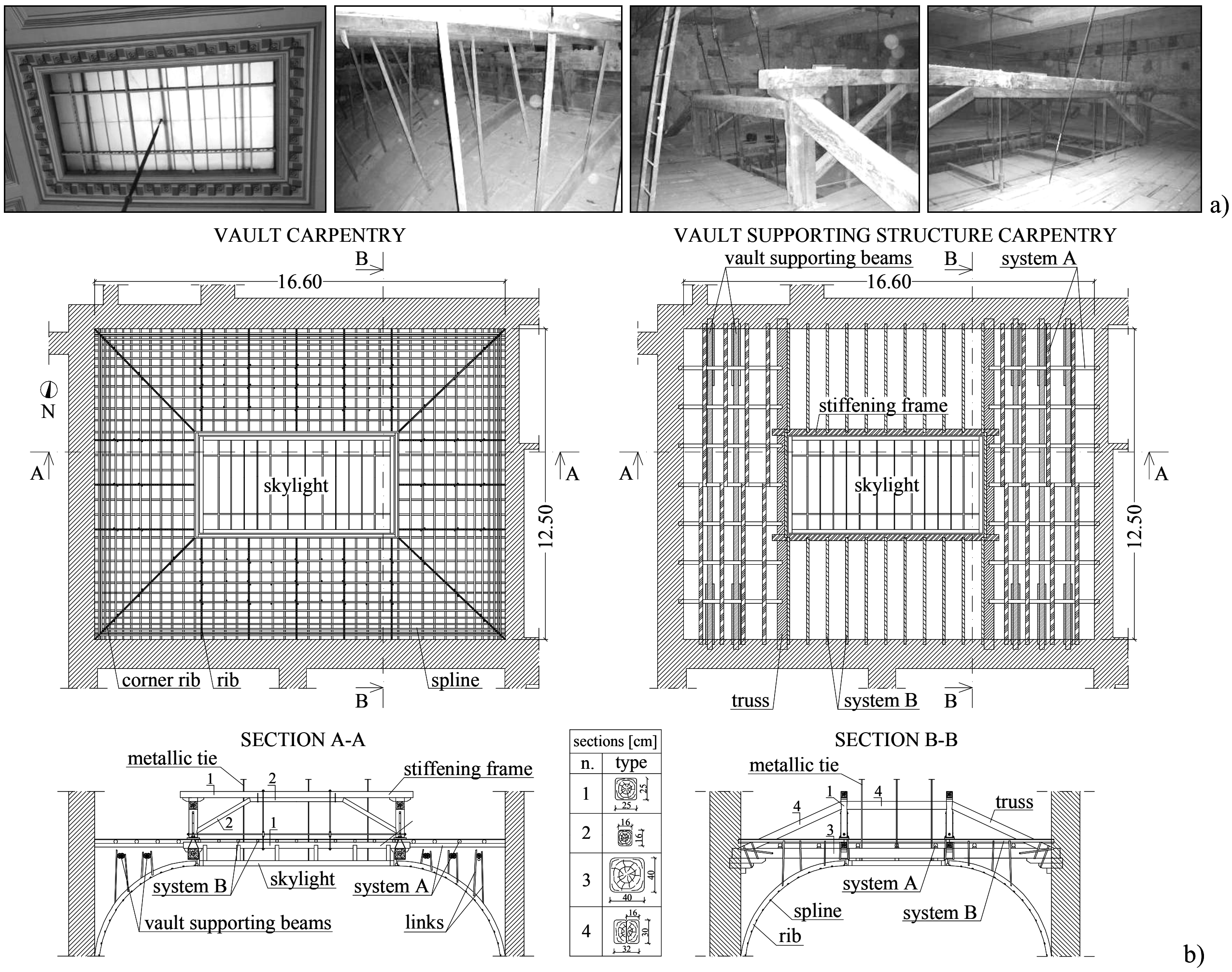


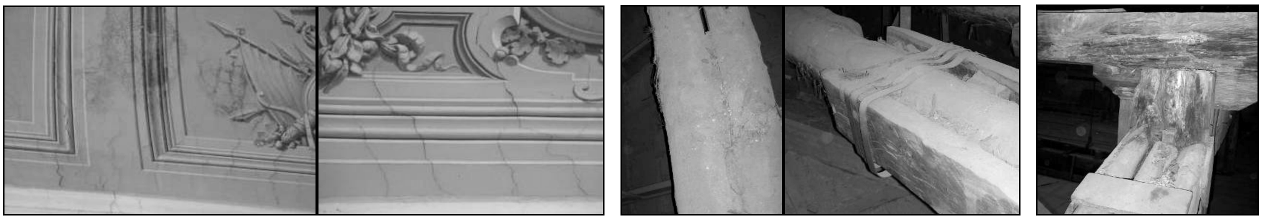
Figure 3: Guard Room (XXIX): a) Photographic survey; b) Carpentries and structural sections [m]

Vault Supporting Structure It is composed by a beam floor with wooden planks, supported by two trusses and two stiffening frames, placed above the skylight perimeter and arranged, respectively, along the minor and major span of the floor (Fig. 3a, b). The floor is realized by the following frame units (Fig. 3b):

- *System A*: grid of beam elements frames with circular cross-section, 15 cm diameter. The primary layout consists of 7 beams, located at the both sides of the floor along the major span; they are supported by the masonry walls at one end and to the truss ties at the other end. The secondary elements are arranged parallel to the tie beams.
- *System B*: squared elements, 10×10 cm^2 sized, located at both sides of the floor, along the minor span, supported by the trusses stiffening frames at one end and the masonry walls at the other end.

Furthermore, 5 vault supporting beams are arranged below the floor beams, along the minor span of the floor (Fig. 3b). Each one is composed by two trunks placed side by side at the mid-span for about 3 m length, connected each other by large nails. Each trunk has a circular cross-section, 20 cm diameter, and is strengthened by thick planks located next to the supports to the walls. The planks are connected to the beams by metallic plates. The beam located at the east side is stiffened by means of longitudinal secondary element and inclined struts, 15 cm diameter.

Failure Diagnosis and Visual Grading Concerning the wooden species identification, ribs, splines and links are made of poplar, whereas all timber elements of the vault supporting structure are made of chestnut, hardwood largely used in the South of Italy. Visual inspections have evidenced that the timber skeleton of the vault is in a proper conservation state. Contrary, wide water infiltrations have been detected in several zones at the intrados of the vault, where many humidity spots and fissures are highlighted, due to seepage from the above r.c. roof (Fig. 4a). With regards to the vault supporting beams, the inefficiency of connection among the timber trunks have been evidenced and the unfastened metallic stirrups, through which the thick planks should be jointed at the beam ends, do not guarantee the strengthening function (Fig. 4b). On many elements of the trusses, stiffening frames and floor beams, natural defects of the material have been detected, as knots, shakes and longitudinal fissures due to the shrinkage. Furthermore, some timber elements of the trusses are locally rotten or subjected to biological attacks, as the king post located at northern-west and the strut which converges to it (Fig. 4c). The latter one is realized by three elements placed side by side, inefficiently connected each other by means of nailed wooden planks. Finally, the planks of the floor are disjointed to the below structural elements and they lack in many parts. All structural elements have been classified in third category class, according to UNI 11119 (2004).



(a) (b) (c)

Figure 4: Guard Room (XXIX): a) Humidity spots and fissures of the vault fresco; b) Connection inefficiency of the vault supporting beams; c) Biological attacks of truss king post

Structural Modeling In Fig. 5 the 3D geometrical models of the structural systems are depicted. They have been set-up by means of the SAP 2000 v. 11 software, using frame elements.

Generally, due to high level of variability and irregularity, which is peculiar of the ancient timber systems, the geometrical models are necessary affected by some approximations, in particular relating to the elements shapes and connection types. It simplifies the structural rendering preserving the real mutual contribution of each unit to the overall behaviour of the complex structure.

In order to examine the stress and strain states during the whole life of the structure from the beginning until today, different load conditions are analyzed, which the structure was supposed to

have undergone, starting from the ones corresponding to the successive erection stages up to the actual service condition. Concerning the mechanical characterization, for the structural models related to the erection phases of the structure the material is modelled as "new timber", assuming the mechanical properties according to UNI 11035-2 (2003) standard. Besides, considering that the timber could be affected by working lacks and degradation together with the creep during the service life of the structure, the material is modelled as "ancient timber" in the phases related to the present state. Therefore, the increment of deformation during the service life is evaluated taking into account the combined effect of the reduction of the elastic modulus due to the wood degradation, corresponding to the third category class of UNI 11119 (2004) code, and the creep for the worst climatic condition, according to Eurocode 5 (EN 1995-1-1, 2004) (Grippa 2010).

In this perspective, different phases and corresponding structural models have been identified, such as: 1) Erection of the structure (new timber, only dead load is considered); 2) Whole structure (new timber, all permanent loads are applied); 3) Service conditions (new timber, the live loads are added); 4) Whole structure (ancient timber); 5) Service conditions (ancient timber). Aiming at evaluating the efficiency of the metallic ties for the vault suspension, the following phase has been also analyzed: 6) No metallic ties (ancient timber; all permanent loads are applied).

With regards to the load analysis, for the vault the permanent load *G* is due to the contribution of the lathing, the stucco and the plaster. The total thickness of the layer is about 7 cm. Altogether the unit weight can be considered as equal to 16 kN/m^3, corresponding to 1.12 kN/m^2. Such load has been applied as a distribution of forces concentrated at the grid nodes, adopting the criterion of the influence area enclosed between the spanning of ribs and splines. The variable actions *Q* are determined on the basis of Eurocode 1 specifications (EN 1991-1-1, 2002).

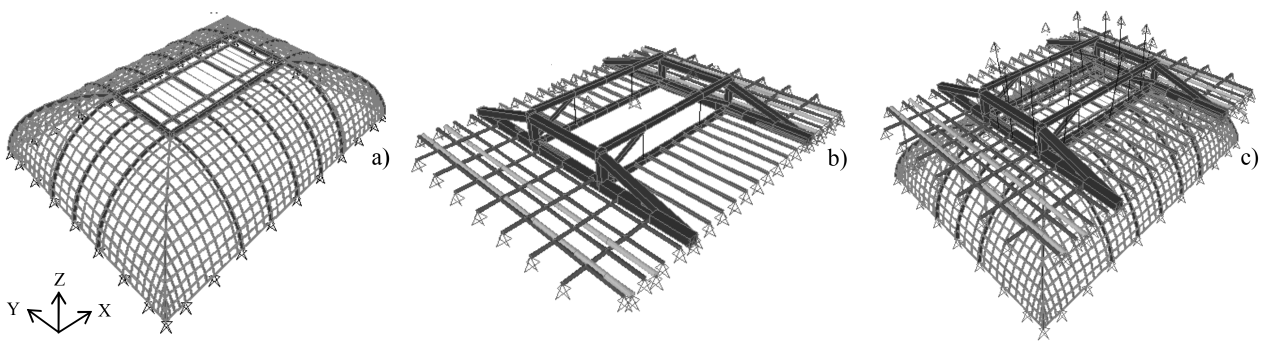


Figure 5: Guard Room (XXIX) – 3D models: (a) Vault; (b) Vault supporting structure; (c) Whole structure

Numerical Analysis The analysis of the vault, with reference to the YZ mid-section, is presented in Fig. 6a, where the deformed configurations are depicted at each phase of life and the stress state related to the Model 4 is described in terms of Moment (M), Shear (S) and Axial force (A).

It is worth noticing that the combined effect of creep and material degradation amplifies the displacements of about three times (Model 2 versus 4); instead negligible deformations are due to the application of the live loads on the floor beams above. Almost all the wooden links which connect the ribs to the upper floor work as struts. Therefore the vault shows a flattening at the upper part and horizontal deformations in the curved part, near the masonry supports; however, the maximum vertical and horizontal displacements are smaller than 3 cm, which does not compromise the preservation of stuccos at the intrados. At the perimeter elements of the vault crown, the beneficial effect of the suspension by metallic ties to the upper r.c. roof is evident by comparing the Models 4 and 6. The vertical deformed shapes of the truss tie beam (Fig. 6b) and of the inferior beam of the stiffening frame (Fig. 6c), together with the internal forces distributions, emphasize that the removal of the metallic ties (Model 6) produces notable increments of deflections and especially of stress. However these elements accomplish the deformation and strength requirements, according to Eurocode 5.

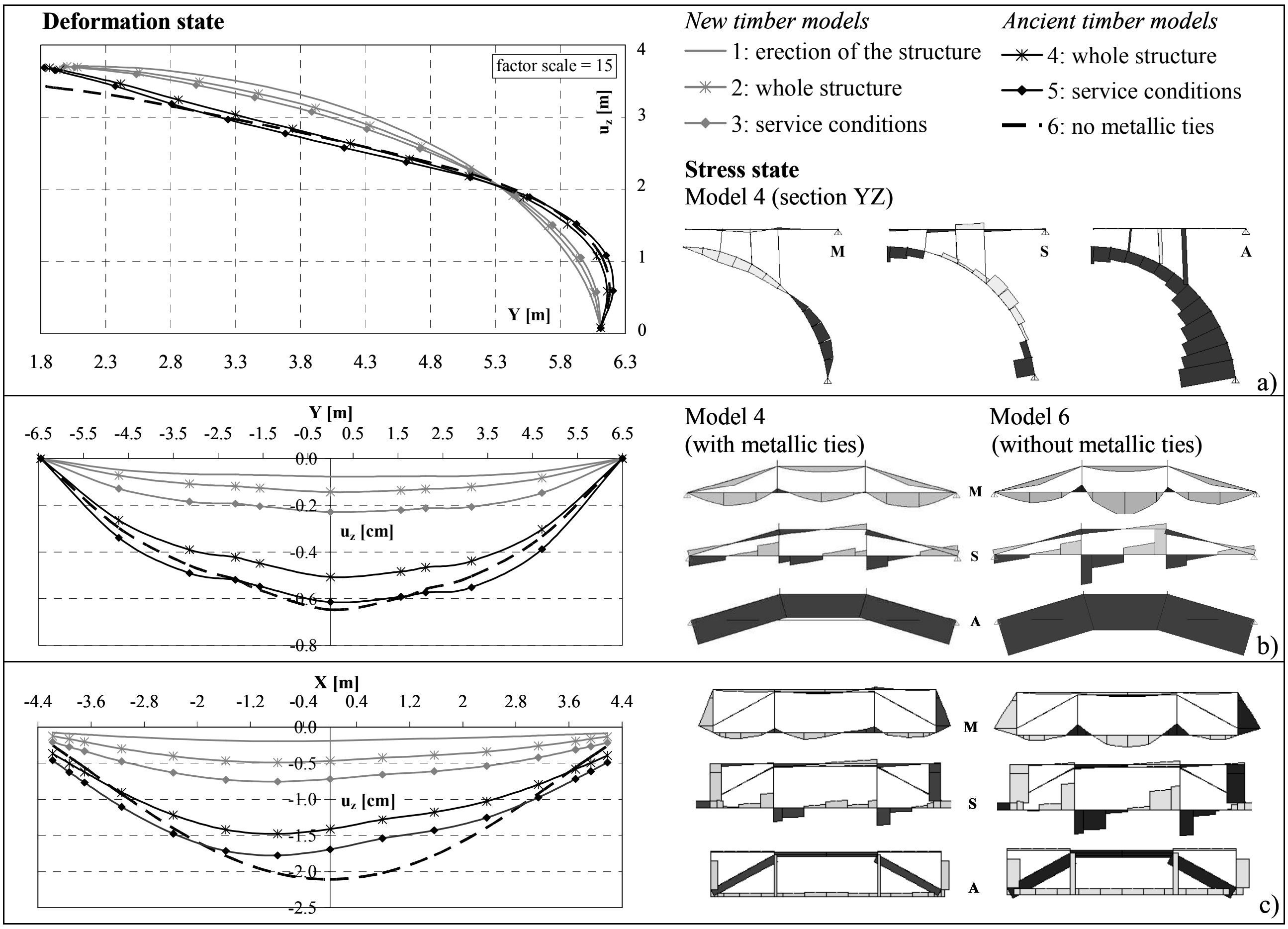


Figure 6: Guard Room (XXIX) – Numerical analysis: a) Vault; b) Truss; c) Stiffening frame.

Conclusions

The timber roofing structure which covers the Guard Room (XXIX) of the Historical Apartment of the Royal Palace in Naples has been selected as study case for exemplifying the methodology for a comprehensive analysis, consisting in geometrical survey, mechanical characterization and numerical elaborations. The investigations show that the vaulted ceiling is generally in good conservation state and exhibits no structural damage. However its preservation and the safeguarding of the frescos at the intrados imply the local restoring of the static function of the elements of the upper supporting structure, required for biological degradation and connections inefficiency.

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