Technology, Diagnosis and Structural Assessment on Timber Composite Beams in Venice Arsenal at the Biennale

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Abstract In the architectural and cultural heritage of the Arsenale of Venice, the authors have worked on several interventions for diagnosis and recovery of roofs, foundations and floors of the so-called "woods of Venice". The work refers to the complex of the “Sale d’Armi” located in the central area of the Arsenale, currently used as exhibition space for the Biennale of Venice. The original nucleus (1460) was used as weapons deposit of the Serenissima. The South “Sala d’Armi”, three buildings on two levels realized in the 17th century, were rebuilt after the fire of 1728. This article describes the diagnostic assessment, including dendrochronological and mechanical assessment, carried out in one of these buildings, the largest one, a large room at full height, which currently preserves original timber elements left in place after the fire: composite beams belonging to a timber floor supported by timber columns. The paper focuses on a very interesting construction system such as the historical composite wooden beams. This technology, although in frequent use in different parts of Italy for the realization of tie-beams of the trusses that were covering large spans, can be found specifically in the area of Venice for the construction of timber floors during the 17th century.

Keywords: constructive technology, composite beams, timber floor, burned structures, diagnosis NDT, dendrochronology

1 Introduction

The present study focuses on a particular construction technology adopted in 17th-century carpentry which consists on the compositions of wooden beams, also called composite beams. This construction system was designed to cover large spans. The use of this technology in the tie-beams of large span wooden trusses is not uncommon.

Of particular interest are those of the Arsenale of Venice. The construction technique analyzed in this study, on the other hand, concerns its application in timber floors in buildings belonging to cultural heritage. The case of the Sale d'Armi beams is reflected in the peculiarity of the construction system present in the city of Venice and in other parts of Italy, as for example in the cities of Ferrara and Florence, in the Renaissance buildings. This article, after an analysis of these constructive systems, describes an unusual intervention on one of the buildings of the "Sale d'Armi" of the Venice Arsenal which is the largest building in the system, a single large room at full height, which currently has timber elements left in place after the fire. These are beams belonging to a timber floor supported by timber columns. The diagnostic assessment carried out were necessary both to understand the behavior of the beams and - mainly - for the extensive area of charred wood resulting after the fire. The research activities, aimed at evaluating the state of preservation and identifying the mechanical strength of the beams, were carried out according to the indications of the Italian Technical Standards (UNI 11119: 2004 and UNI 11138: 2004). This preliminary assessment before the design of the consolidation intervention was presented with a multi-disciplinary approach that made it possible to optimize the use of the available resources and to avoid further damage to the existing structures that remained as evidence of the cultural heritage and of the techniques and technologies present in Venice. This work has constituted the base for a complex restoration of the building, currently used as exhibition space for the Biennale of Venice and as multipurpose cultural space.

2 Historical background

The Venice Arsenal, with its 48 acres of extension and a history that goes back more than 800 years, is an extraordinary subject of study of constructive techniques and of experimentation in the development of restoration methods. The wooden roof systems in are the most precious example of almost 700 years of building technology that was strictly linked and influenced by the development of naval shipbuilding industry. Since 1983 the Venice Superintendence (National Board of Antiquities) has been working and in-vesting many resources on a program of study of the Arsenal, concentrating especially on roofs structures (Menichelli et al., 2009; Bertolini, Marzi, 2018).
One of the aspects that contribute in determining the extraordinary cultural interest of the Venice Arsenal is the dimension and richness of the material, constituting a witness of architecture and constructive technologies for naval shipbuilding.
The assessment was mainly focused on the roofing structures of numerous buildings located in the Arsenale area: the tie-beam was a constant. This element, the longest within the truss system, looks like a composite beam, with different connection systems used to connect different wooden elements.

Fig. 1 Aerial view of the city of Venice (a), the Arsenale complex (b) and the Sale di'Armi (Room E highlighted in orange) (c)

The paper focuses on the South Sale d'Armi, in particular the "E" building (Fig. 1). The complex of the South and North Halls consists of two imposing two-story buildings. These buildings, whose original nucleus dates back around 1460, constituted the repository of the most important military armaments of the Serenissima Republic and were also used for representation purposes in occasion of visits of particularly important guests. With the adjacent Artillery building, the Halls of Arms, Sale d'Armi, constituted the symbol of the war power of Venice "by land and sea". It was accessible only through the monumental Artillery Gate, built around 1560 - attributed to Sanmicheli - to separate the artillery sector from the other functions of the Arsenale. The Sale d'Armi South, built after the North Hall facing the dock, presumably date back to the mid-17th century. They were rebuilt in the mid-1700s, after a fire dating back to 1728. They are divided into three buildings (E, F, G). The overall dimensions of the South "E" sector, on two floors, are 2300 m^2 (Fig. 2-3).

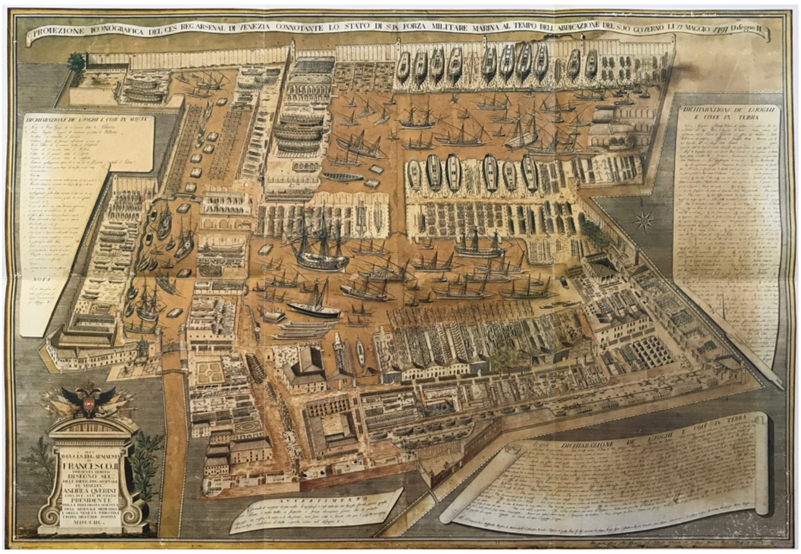

Fig. 2 Iconographic representation of the Arsenale of Venice, G. Maffioleti, 1797 (from U. Pizzarello, V. Fontana, *Pietre e legni dell'Arsenale di Venezia*, L'altra Riva, Venice 1983)

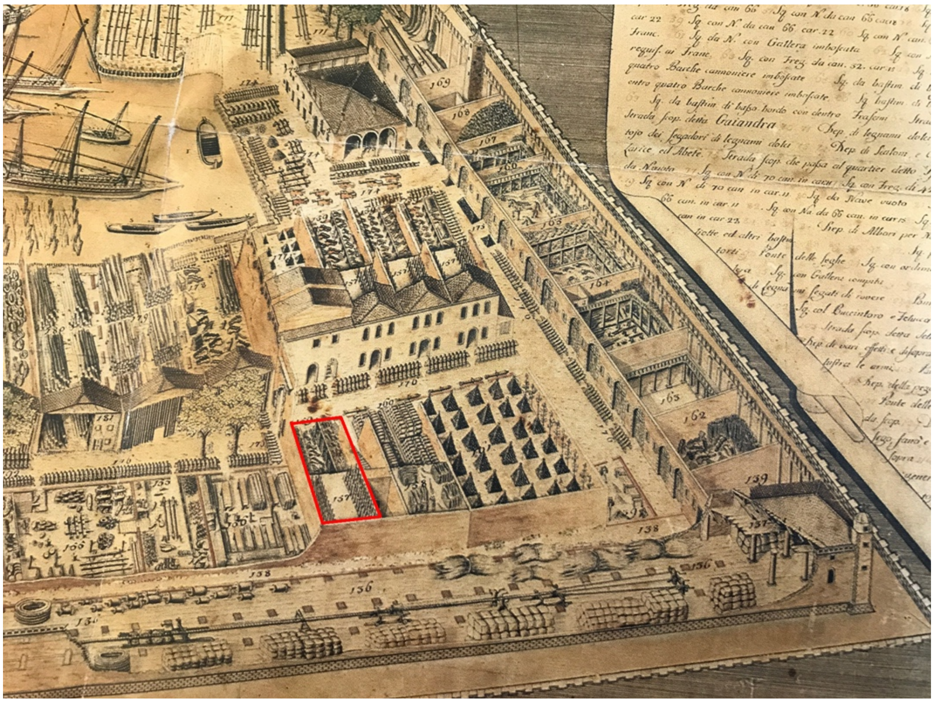

Fig. 3 Iconographic representation of the Arsenale of Venice, G. Maffioleti, 1797 (from U. Pizzarello, V. Fontana, 1983). Highlighted in red the Sala d'Armi South, building E.

In 1964 the Arsenale ceased all activity and the Sale d'Armi were at first used as warehouses by the Navy and then abandoned.
Since 2007, having survived almost intact in the load-bearing structures, after the passage of management to the Venice Biennale, the block of buildings has undergone a complete restoration which foresees its new destination as exhibition, show and cultural spaces linked to the activities of the Biennale (Fig. 4).

Fig. 4 View of the Sale d'Armi South, 1980's (left) (from U. Pizzarello, V. Fontana, 1983); Sale d'Armi North and South during the recent restoration.

The analyzed “E” building is the largest block in the sector. It currently looks like a single large full-height nave, due to the collapse of the intermediate floor due to the 18th-century fire.
As evidence of the architectural importance of the building, the two large wooden beams, object of the present study, were still preserved on site (Fig. 5).

Fig. 5 Interior view of the Sala d’Armi “E” (left), detail of the burned wooden beam with wooden column (right). (Photo D. Ferrante, 2019)

3 Constructive technology

The definition of "composite beam" can be found in historical documents or treatises with reference to a generic term of "*chiavon*", or big beam. With this term we mean a wooden element made through an appropriate assembly of different wooden elements that allow you to cover large spans with correct structural behavior.
Composite beams are quite frequent in the typology of large wooden trusses with particular regard to the longest element of the construction system which is the tie-beam. At the Arsenale of Venice, in many “Tesoni” buildings, the tie-beams are made with large composite beams that simultaneously served to perform the function of a tie-beam. In some cases, these elements also functioned as beams to mast ships.
The singularity of the beams analyzed in building "E" is that they are composite beams used as support for the main floor.
These beams are made of five overlapping wooden elements: a tie-beam made of two elements side by side, two rafters elements positioned symmetrically to the extrados of the beam, an element that functions as a block or key to close the system.
Another characteristic of the analyzed composite beams is that the elements that compose them are made with different wood species.
The general characteristic of composite beams is the curvature of the tie-beam which corresponds to a counter-deflection imposed with respect to that resulting from the loads. Therefore, there is a curvature towards the upper part.

The connections between the different pieces that make up the construction type are made with cutting indentations. These shapes between the parts in contact prevent the overlapping elements from sliding. Through nails (metal nails inserted from the extrados and riveted) confirm the robustness of the system. These rivets often are joined by metal straps (*reggette*) that collaborate in their assembly (Fig. 6).
Each beam covered a span of about 11.80 m, had a section of 30 (base) x 68 (height) and originally had two wooden columns placed approximately at the distance of 1/3 from the support.

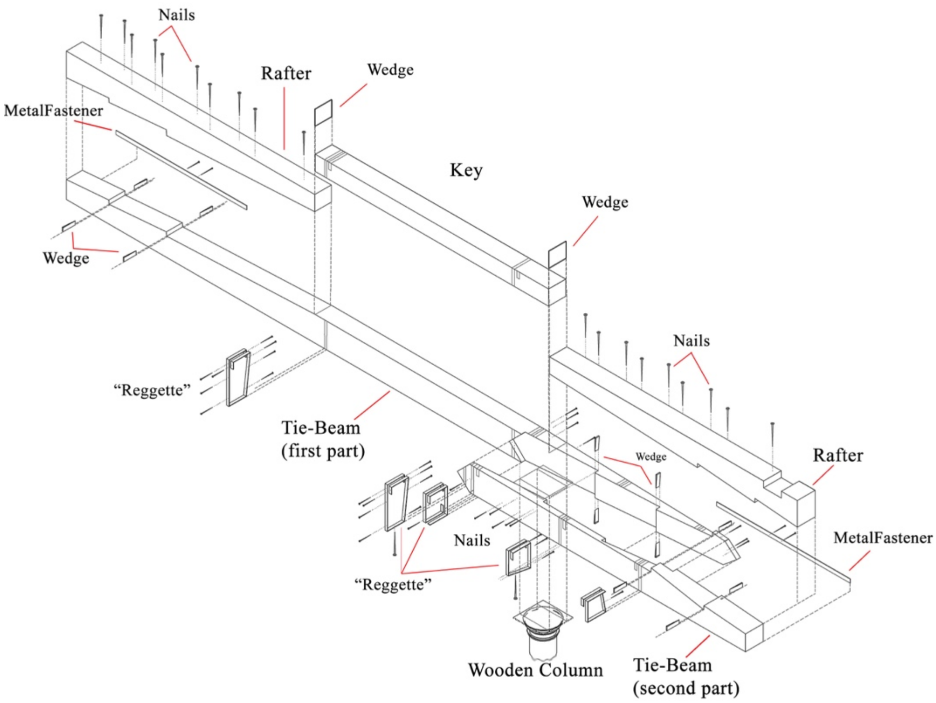

Fig. 6 Axonometric scheme of the different parts constituting the composite beam with the wooden column.

The two composite beams, which have remained in the "Sala d'Armi" building "E" building today, have extended traces of fire.
A single wooden column with Doric capital is currently present in the first beam, with a height of about 4.30 m (Fig. 7).

Fig. 7 Interior view of the Sala d'Armi "E", composite beams and wooden column (Photo D. Ferrante, 2019)

In the tradition of construction consolidated within the Venetian territory, horizontal wooden structures assume specific aspects, material, structural, formal and the whole construction organism connection, forming a complex technological device. The fieldwork of a large number of existing floor structures, dating back to the 14^{th} and 18^{th} century, has allowed to highlight the characters of both the individual elements and the "floor system" as a whole (Scappin L., 2015).

In Italy, this construction technology is very widely reflected in the wooden floors of the Renaissance city of Ferrara (Giunchi E., Malvezzi R., and Russo M., 2001-2002; Giunchi E., Malvezzi R., Russo M., Alessandri C. and Fabbri, R., 2004). The Ferrara composite beam, which we find widespread within important buildings of the 15^{th} - 16^{th} centuries, is often made of four or six pieces. The singularity of these beams is their slimness. In particular, the six-piece beam consists of the tie-beam, the two rafters, the dowel or key inserted centrally, and to complete two "shoulders", they contribute to characterize the geometry.

A wide documentation of the composite beams can be found in Italian treatises. It is interesting to recall how in the 15th-16th centuries in the Atlantic Codex of Leonardo da Vinci the aspects of construction technique and technology are investigated, such as the possible solutions to impart the curvature to the tie-beam and to create cuts with adequate connections between the different components (Fig. 8).

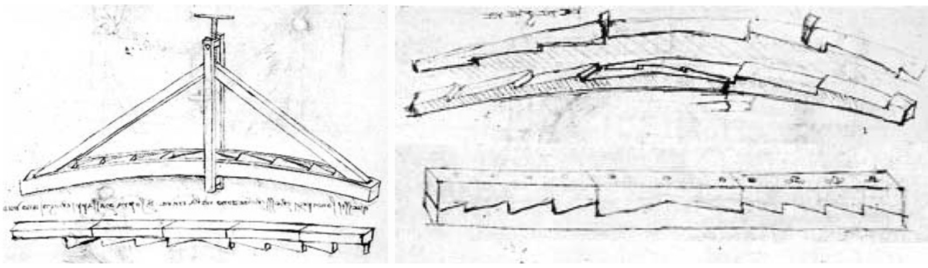

Fig. 8 Leonardo's "trestle" for bending composite beams interior (left); Leonardo's sketches (right) (from Leonardo Da Vinci, Il codice atlantico della Biblioteca Ambrosiana di Milano, trascrizione critica di Augusto Marinoni, Giunti, Firenze 2000)

4 Diagnosis

4.1 Technological survey

The technological survey for assessing the state of conservation and geometry of connections has basically regarded:
- diagnosis, intended as the complex of on-site and/or laboratory techniques, which have as their object the survey of the original natural characteristics of wood (wood species, physical-mechanical properties, defects) and those acquired after the construction (biotic decay, breakages, deformations);
- timber grading according to resistance, using the results of the diagnostic phase to define the structural quality of the wooden elements according to "categories" from which the values of the main physical-mechanical characteristics used in the calculation of structural safety are obtained;
- assessment of the functionality of the joints, which is of fundamental importance for the proper functioning of traditional timber structures, since structural stability problems often stem from the inadequate capacity of the joints to transfer the forces from one element to the other;

These types of surveys went alongside with instrumental investigations, with the help of resistance drilling for wooden elements whose state of conservation needed to be verified. Furthermore, also the constructive survey was integrated with the use of resistance drilling to verify the thickness of the different parts constituting the joint, a very important indication for the assessment of the state of conservation and mainly of the stability of the structure.

For the Venice Arsenal, survey charts were used, which constitute a "reading grid" for the identification of all the features that allow to fully defining the technical solutions originally adopted for the construction of the structure and for the identification of all the decays (these obtained through the recalled diagnostic activity).

The diagnostic assessment mainly concerned the timber elements of the main supporting structure of the trusses, to which the investigations on secondary elements were added (Fig. 9).

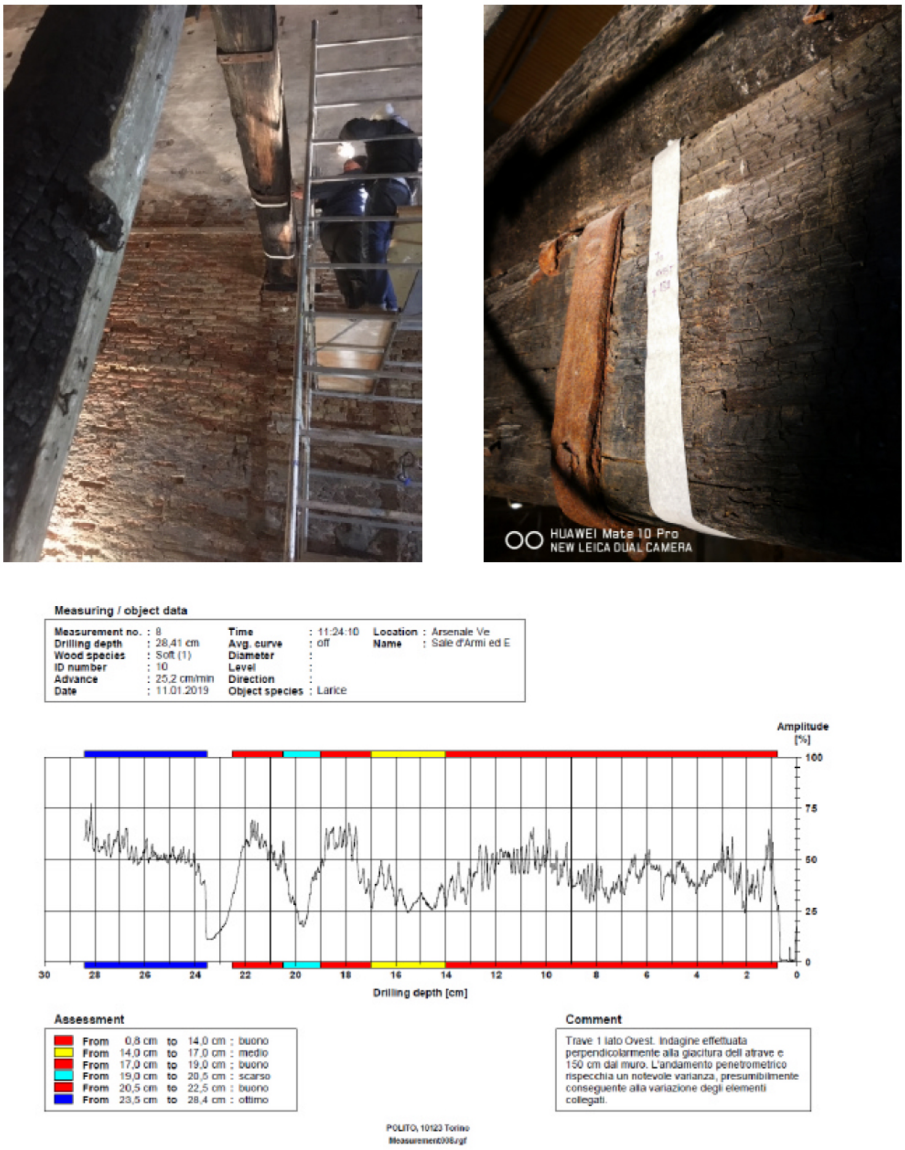

Fig. 9 Diagnostic survey on the composite beam. Overlapping of the different wooden elements composing the beam. Example of resistance drilling carried out on the beam.

The purpose of the inspection was to obtain the information listed below related to the wooden elements being investigated, in order to assess their integrity and mechanical performance. In particular, data was collected regarding:

a) wood species;

b) wood moisture content and any humidity gradients;

c) biological risk class for wood, according to UNI EN 335-1 and UNI EN 335-2;

d) geometry and morphology of the wooden element, with indication of the position and extent of the main defects, decay and any damage present;
e) position, shape and dimensions of critical areas and sections;
f) classification according to the resistance of the element as a whole and/or of the individual critical areas, according to the UNI 11119 standard.
The first three phases allowed to establish if the structure was subject to biotic degradation by specific xylophagous organisms. All the other evaluations allowed the assignment of a resistant profile for each of the elements constituting the examined structure. This has constituted the base of the restoration works.

4.2 Dendrochronological investigations

Xylotomy (UNI 11118: 2004) and dendrochronological (UNI 111141: 2004) investigations aimed at identifying the wood species used and dating the two composite beams, involved almost all the elements, with the exception of the key of the beam T2 (Table 1).

Table 1 Characteristic of the examined elements

Composite beam	Element	Species	Lenght	sapwood	Last ring
T1	Rafter side W	*Abies alba* Mill.	172 rings	undifferenciated wood	**AD 1579**
T2	Rafter side W	*Abies alba* Mill.	57 rings	undifferenciated wood	**AD 1501**
T2	Rafter side E	*Picea abies* Karst.	185 rings	undifferenciated wood	undated
T1	Rafter side E	*Abies alba* Mill.	87 rings	undifferenciated wood	**AD 1550**
T1	Key	*Larix decidua* Mill.	88 rings	absent	undated
T1	Tie-beam side E	*Larix decidua* Mill.	109 rings	28 rings	undated
T1	Tie-beam side W	*Larix decidua* Mill.	124 rings	25 rings	undated
T2	Tie-beam side E	*Larix decidua* Mill.	73 rings	22 rings	undated
T2	Tie-beam side W	*Larix decidua* Mill.	86 rings	18 rings	undated

The tie beams were all made of larch wood (*Larix decidua* Mill.), as well as the only key examined; for the rafters, instead, fir (*Abies alba* Mill.) and spruce (*Picea abies* Karst.) were used. The dendrochronological investigations carried out following the classic procedures (Baillie 1982, Fritts 1976, Schweingruber 1982), led to the date of the only three rafters in fir. These elements, all missing the outermost rings, partly removed with the processing of the trunks, and partly deteriorated as a result of the carbonization, provided only the terms after which the matrix plants were felled (Table 1). The year AD 1579 constitutes the common *terminus ante quem non* for the felling.

No dating has been identified for the other examined wooden elements. Unfortunately, the absence of dating for the tie-beams, all with sapwood, and, in two cases, also with traces of the bark, does not allow us to establish from a dendrochronological point of view whether the elements of fir represent reused wood.
However, it must be underlined that the larch series do not match with the other dated series in the Arsenale area. This seems to suggest that the larches used for the tie - beams of the composite beams do not refer to the felling phases identified so far for the Arsenale compound.

5 Structural assessment

The two beams are composed by four main structural elements. The intrados portion is a two-pieces composed tie-beam. The connection between the parts is provided by means of horizontal steel pins and several notches, in addition to steel stirrups nailed to the beam. The tie-beam is subjected to tensile stresses. The tie-beam do not show, contrarily to other examples, a significant curvature. In addition, it can be noticed that each beam was supported by two vertical wooden pillars, although only one of them is survived. The extrados of the beam is composed of a central rectangular key piece surrounded by two symmetrical rafters. These three parts are subjected to compressive stresses. The extrados plan shows a series of regularly spaced big nails (rivets) which, together with notches, guaranties the transmission of shear stresses at the level of the neutral plane. A three-dimensional finite element model has been set up to assess the level of stress and amount of deformations of the two timber beams. The model account for the presence of the different structural elements of the composed beams, and for the presence of the survived pillar. The interaction between the parts has been accounted for by means of no-tension structural interface special elements. The structure is analyzed under the effect of dead weight only, in order to assess the feasibility of conservation of the beams, accounting also for possible degradation due to partially burned surfaces. The state of coaction in the structure mainly depends on the actual procedure followed during the assembling of the composed beams, in addition to the rheologic behavior of the parts and interfaces. Although it is very difficult to provide a precise picture of the present state, some parametric analyses have been carried out by considering different imposed deformation to the rafters and central key-part.
As a result, given the level of stresses and deformation of the beams, their conservation is strongly advised (Fig. 10).

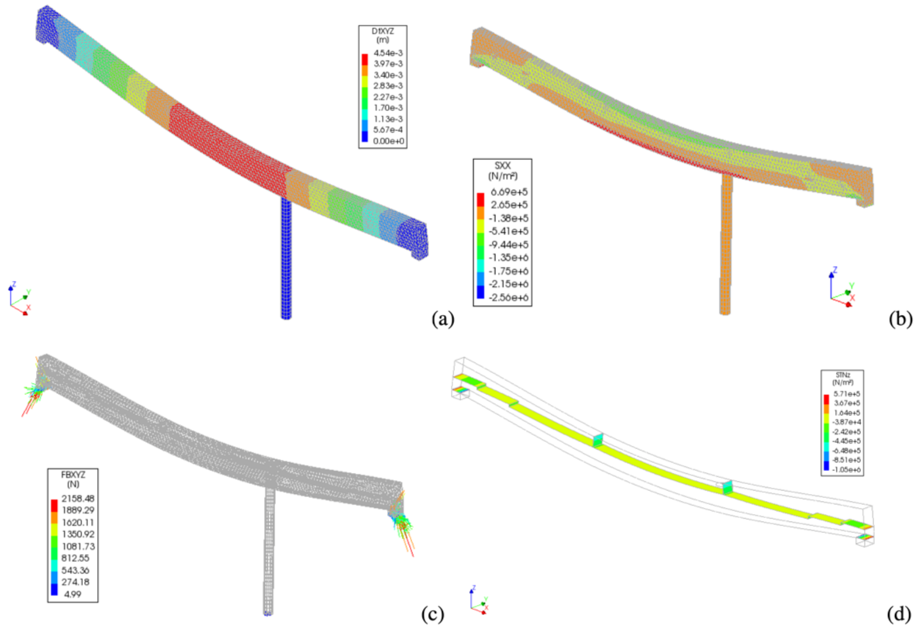

Fig. 10 Finite element analysis results: deformed mesh (a); normal stress component along the beam axis (b); reaction forces at the boundary (c); tractions in correspondence of the interfaces (d).

6 Conclusions

The main assessment conducted on the timber elements of the composite beams of the floor of the Sala d'Armi "E" at the Venice Arsenal concerned: the technological valuation of the components and their mechanical resistance, the dendrochronological investigation, the structural evaluation. The results of these multi-disciplinary activities have led to the validation of the various timber members in good condition and mechanical response. The diagnostic survey has constituted the base for the following restoration phase.

The proposed case-study represents an example of great interest among the timber floor structures realized with the composite beams' constructive technology.

Acknowledgements The Biennale of Venice is gratefully acknowledged.

References

Baillie, M.G.L. (1982). Tree-ring dating and archaeology, London – Canberra, 1-274.

Bertolini-Cestari, C., and Marzi, T. (2018), Conservation of historic timber roof structures of Italian architectural heritage: diagnosis, assessment, and intervention. *International Journal of Architectural Heritage*, 12:4, 632-665.

Fritts, H.C. (1976). Tree ring and climate, Academic press, London-New York-San Francisco, 1-576.

Giunchi, E., Malvezzi, R., and Russo M. (2001-2002), Travi composte in legno nella Ferrara rinascimentale: indagini conoscitive e proposte di intervento. Thesis. Università di Ferrara.

Giunchi, E., Malvezzi, R., Russo M., Alessandri, C. and Fabbri, R. (2004). High Technology and Structural Insight in the Wooden Composite Beams of the Renaissance Architecture in Ferrara. In Bertolini-Cestari, C., Marzi, T., Seip, E., Touliatos, P. (editors). Interaction between Science, Technology and Architecture in Timber Construction, Elsevier, Paris, 513-544.

Leonardo Da Vinci, Il codice atlantico della Biblioteca Ambrosiana di Milano, trascrizione critica di Augusto Marinoni, Giunti, Firenze 2000

Menichelli, C., et al. (2009). Le strutture lignee dell'Arsenale di Venezia. Studi e restauri. *XXV Convegno Internazionale Scienza e Beni Culturali - Conservare e restaurare il legno*, Bressanone, Arcadia Ricerche, 1163–216.

Pizzarello, U., and Fontana, V. (1983). Pietre e legni dell'Arsenale di Venezia, L'altra Riva, Venice.

Scappin, L. (2015). Il solaio ligneo nel 'congegno' dell'edificio storico veneziano: elementi, connessioni e dimensionamenti. In Marzo, M., Rakowitz, G., Nella ricerca. Città/Venezia, Università IUAV, Venezia, 85-109.

Schweingruber, F.H. (1988). Tree Rings. Basics and applications of dendrochronology, Reidel Publishing Company, 1-276.

UNI 11118:2004. "Beni Culturali, Manufatti lignei. Criteri per l'identificazione delle specie legnose ", UNI, Milano

UNI 11119:2004 Beni culturali - Manufatti lignei - Strutture portanti degli edifici – Ispezione in situ per la diagnosi degli elementi in opera;

UNI 11141:2004. "Beni Culturali. Manufatti lignei – Linee guida per la datazione dendrocronologica del legno", UNI, Milano.