VOL. 8, SPECIAL ISSUE (2022)

Remarkable historic timber roofs. Knowledge and conservation practice.
PART 2 - Investigation, analysis, and interventions

TEMA
Technologies
Engineering
Materials
Architecture

Cover illustration: Auxiliary truss for the strengthening of the roof of San Giovanni Battista church, Borno, Brescia, Italy, 1771-81/2020. © Emanuele Zamperini (2020)

e-ISSN 2421-4574
DOI: 10.30682/tema08SI2

TEMA
Technologies
Engineering
Materials
Architecture

e-ISSN 2421-4574
ISBN online 979-12-5477-086-3
DOI: 10.30682/tema08SI2
Vol. 8, Special Issue (2022)

Remarkable historic timber roofs. Knowledge and conservation practice
Part 2 - Investigation, analysis, and interventions

Year 2022 (Issues per year: 2)

Cover illustration: Auxiliary truss for the strengthening of the roof of San Giovanni Battista church (architectural design by P. Castelnovi, structural design by E. Zamperini with the collaboration of G. Sacco), Borno, Brescia, Italy, 1771-81/2020 by E. Zamperini. © Emanuele Zamperini (2020)

Scientific Society Partner:
Ar.Tec. Associazione Scientifica per la Promozione dei Rapporti tra Architettura e Tecniche per l'Edilizia
c/o DICATECH - Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica - Politecnico di Bari
Via Edoardo Orabona, 4
70125 Bari - Italy
Phone: +39 080 5963564
Email: info@artecweb.org - tema@artecweb.org

Media Partner:
Edicom Edizioni
Via I Maggio 117
34074 Monfalcone (GO) - Italy
Phone: +39 0481 484488

TEMA: Technologies Engineering Materials Architecture
Vol. 8, Special Issue part 2 (2022)
e-ISSN 2421-4574

HISTORIC TIMBER ROOFS, A KNOWLEDGE-BASED APPROACH TO STRENGTHENING: THE CASE STUDY OF A RENAISSANCE PALACE IN FERRARA

Lia Ferrari

TEMA Technologies Engineering Materials Architecture
e-ISSN 2421-4574
Vol. 8, Special Issue part 2 - (2022)

DOI: 10.30682/tema08SIo

This contribution has been peer-reviewed.

Abstract

Knowledge is essential to preserve timber roof structures for their historical and architectural value, since it allows to fully understand their cultural significance and actual structural behavior, thus planning specific strengthening interventions. This paper presents the case study of Palazzo Costabili in Ferrara, Italy, to propose a method to plan architectural strengthening intervention on historical timber roof structures based on a detailed knowledge of the structures' features and state. The palace object of this study is characterized by historical timber structures, an expression of traditional local building techniques, which were partially damaged in the 2012 earthquake. Therefore, an in-depth and careful study of the structure was carried out to identify specific parts that needed to be reinforced. A strengthening of the roof structure was thus designed considering the performances of the timber components and their historical-cultural value. More specifically, the timber roof was first assessed to identify the main wood species, the constructive types, and their related vulnerabilities. At the same time, the parts that showed consistent signs of structural stress were later evaluated by specialists using visual and instrumental analysis. Finally, data collected were critically analyzed to better plan the strengthening intervention, considering both the stress state of the single components and their specific weaknesses, in full compliance with preservation criteria and needs.

Keywords

Historic timber roofs, Traditional construction techniques, On-site assessment, Minimal intervention principle, Preservation of cultural heritage.

Lia Ferrari
DIA - Dipartimento di Ingegneria e Architettura, Università degli Studi di Parma, Parma (Italy)

Corresponding author:
e-mail: lia.ferrari@unipr.it

1. INTRODUCTION

In heritage architecture, timber structures are considered witnesses of architectural technology and construction materials of high cultural and historical significance. However, their relevance has been highly neglected in the past, especially compared to the interest and attention paid to the buildings in which they are located [1]. One possible reason for this attitude could be that assessing the actual state of conservation of timber components (and thus their residual mechanical performance) is more complex than simply replacing the wooden elements. Consequently, problems were generally solved in the past by heavily reinforcing the structure with wood, iron, or resins or by replacing not only the decayed parts but the entire timber roof with modern structures and materials. In the 1980s, for instance, the Italian guidelines invited to replace original timber roofs with iron or reinforced concrete structures [2], while preservation of the original roof was allowed only «for reasons of high architectural value» and «in very exceptional situations». This led to consistent alterations of the supporting masonry, strengthened with mortar injections, metal bars, reinforced concrete jacketing, and ring beams [3].

The current approach to historic timber roof conservation is more empirical and respectful of the timber roofs' historical and cultural significance to be preserved as an epitome of old traditional construction techniques with their tangible and intangible features. Thanks to recently developed and improved methods and procedures [4] to empirically analyze existing timber structures, it is now easier to assess their residual mechanical performance and, therefore, to set up more aware and respectful restoration plans. Such a knowledge-based approach needs to be carefully planned at different levels: from the survey of single members and joints (geometry and material consistency) to the interpretation of the structural behavior of the timber structure, considered as a whole and part of the building [5]. Moreover, such peculiar characteristics should be compared with the typical features of similar structures and traditional building skills to better highlight vulnerabilities as well as material (decorations, materials) and immaterial elements to be preserved (construction techniques, structural features).

This approach is useful to assess the actual state of conservation of timber roof structures, to identify the most critical points, and to guide restoration interventions on such structures, usually trying to strike a balance between the preservation of the original material [6] and the respect for the technological conception [7]. Strengthening interventions should always consider the material and immaterial value of the timber roof structure, following the principle of minimum intervention usually recommended in cultural heritage.

This contribution shows how such a knowledge-based methodological approach can be applied to plan timber roof structure strengthening interventions by using the case study of Palazzo Costabili in Ferrara, a historical building featuring timber floors and roofs that are an expression of local construction traditions and techniques. Unfortunately, the palace was severely damaged in the 2012 earthquake and required urgent reinforcement and seismic improvement, especially its historical timber roof. The strengthening intervention started from an in-depth assessment of the actual performances of the timber components, and the reinforcement was specifically designed to preserve the historical value of the roof structures.

2. PALAZZO COSTABILI IN FERRARA

Palazzo Costabili (Fig. 1a) is located in the southeastern and oldest part of the city of Ferrara at the edges of the medieval town, far from the religious and historical center [8]. Despite its marginal position, the palace was a significant building, as testified by the historical figures involved in its construction. The palace was commissioned at the end of the fifteenth century by Count Antonio Costabili (1450-1527), an influential nobleman at the Court of Duke Ercole I of the House of Este. Since he was the ambassador for the Este Family in Milan, the palace is also called "Palazzo di Ludovico il Moro" after Ludovico Sforza, called "il Moro", Duke of Milan from 1494-1499.

2.1. HISTORICAL DEVELOPMENT AND RECENT RESTORATION WORK

According to the date on the original project by Biagio Rossetti (1447-1516), one of the main architects at the court of the House of Este, the palace construction started in 1500 [9, 10]. It was initially conceived as a three-story building organized around a central courtyard of honor with the main entrance on the northern side. It was made up of connected buildings with a double loggia (Fig. 1b), enriched with decorations in white stone by Gabriele Frisoni, who also decorated the monumental staircase with geometric and floral motifs. Next to the stairs, a corridor connects the courtyard to a garden on the eastern side, whereas a grand loggia, on the opposite side of the main entrance, leads to a large park at the back of the building. On the first floor, the upper loggia is composed of a long series of open and blind windows. Nevertheless, only the southern and eastern

Fig. 1. *(a) Aerial view of Palazzo Costabili (image source: Google Earth); (b) three-story building with double loggia organized around the main courtyard.*

sides were completed following the original project. In 1503, Rossetti and Frisoni handed the works over to Maestro Girolamo Pasini and Maestro Cristoforo. Still, one year later, the construction was interrupted, and the northern and western buildings remained single-story buildings without stone decorations [11]. Even if it was never completed, Palazzo Costabili could be considered today as one of Ferrara's most ambitious palaces of the Renaissance period.

After the sixteenth century, the palace changed ownership several times and was split among different owners, thus undergoing substantial modification until it fell into severe decay. In 1920 the palace was confiscated and purchased by the Italian government, and in 1930 it was destined to become the National Archaeological Museum of the Civilization of Spina, officially opened in 1935 [12]. Since then, the museum has showcased all archaeological findings from the province of Ferrara, especially those of the town of Spina, one of the most significant urbanized centers in the region between the sixth and third century BC.

As the building changed its intended use, restoration works were carried out between 1932 and 1935 to fix intrinsic structural deficits due to its architectural conformation [13, 14]. Further strengthening interventions were carried out during the last decades of the twentieth century. Today most of the original vaults and wooden floors were reinforced with metal elements or reinforced concrete slabs.

3. THE TIMBER ROOF STRUCTURE OF THE PALACE

The roof of Palazzo Costabili is characterized by different types of timber structures, while the covering layers are homogeneous, consisting of wooden joists and flat tiles (*pianelle*), while the outside features curved tiles. Such differences in timber seem to be related to the different widths between supports and the articulated configuration of the roof, with complex intersections, differences in height, and misalignment between walls and ridge rather than to the different periods of construction. General architectural features – like the use of open joint trusses [15] and the so-called *alla palladiana* or queen trusses [16] – can be traced back to the 16th century and Ferrara Renaissance architecture. Proof of this is the *trave composta* (using the same technique as a composite beam) employed here in the large-span rafters or purlins typical of local Renaissance construction [17]. This technique consists in connecting more timber beams through precise notches, thus obtaining a single structural element. A recent study showing that the distance between trusses has increased over centuries, changing the configuration of upper layers [19], confirms our dating hypothesis for the timber structures of Palazzo Costabili, as its trusses are shortly distanced (170-210 cm). It should be noted that purlins were not employed here, and joists relied directly on trusses parallel to the ridge. At the same time, flat tiles were arranged with the shorter side parallel to the ridge, which unfortunately caused them to slide down and rotate over time. Over the centuries, the distance between trusses was later increased, and the purlin layer was inserted so that joists became perpendicular to the ridge and the flat tiles more stable [18]. Due to these architectural features, despite the lack of archival documentation, we can posit that most of the timber roofs of Palazzo Costabili date back to the construction of the building itself. However, further analysis – such as a reading of the masonry on which the roof structure rests or dendrochronological studies on the main wooden members – should be carried out to verify the hypothesized dating.

Some parts have, however, been partially modified and consolidated over time. Joints, originally obtained with precise notches and thus featuring few metal connections [16], were progressively reinforced with metallic elements (nails, iron strips, straps, etc.). Even the connection with corbels, widely used in Ferrara's timber structures to reduce deformation, has been improved using metal strips and nails. However, no space was left between the timber members and masonry, generating weak points subject to progressive deterioration because of moisture. More invasive interventions were carried out between 1992 and 1993, as shown by archival documentation [19, 20]. Decayed parts of timber members (especially those in contact with masonry), which deteriorated due to moisture or fungal attack, were removed, and Ø24 metal bars were inserted with epoxy resin to strengthen the joints of trusses or rafters. Moreover, several secondary members have been replaced by new spruce joists (10 cm x 10 cm) or purlins (20 cm x 20 cm) with a bitumen coating at the extremities. One year later, in 1994, strengthening interventions concerned the southern gable roof of the building: a steel cross bracing was inserted [21]. In 1999, the timber structure of the southeastern block was subject to other invasive reinforcements. The decayed extremities of the rafters were replaced by epoxy resins prosthesis and strengthened by internal Ø28 metal bars (Fig. 2a), while Ø24 metal bars were inserted along the rafters to improve the connection between the components of *trave composta* and metal tie-rods were used to enhance the connection between rafters and the central wall (Fig. 2b). The queen trusses of the opposite pitch were also reinforced by the insertion of flitch plates at the joints and a double layer of metal tie-rods for the connection with the central wall.

3.1. IDENTIFICATION OF TIMBER ROOF TYPES

Among timber roof structures, areas with a common morphology (e.g., similar span and type of load-bearing structure) have been identified. In the following sections, a short description of each one is provided to highlight their main features (Fig. 3).

3.1.1. TIMBER PURLIN ROOF

The timber purlin roof is composed of 540-590 cm long beams with a cross-section of 25 cm x 18 cm, arranged parallelly to the ridge at a distance of about 160 cm. This type of roof is employed for small areas. To cover larger spans (790-880 cm), two different solutions were adopted when the palace was built: a rafter beam of a similar section was inserted as intermediate support or the

a) b)

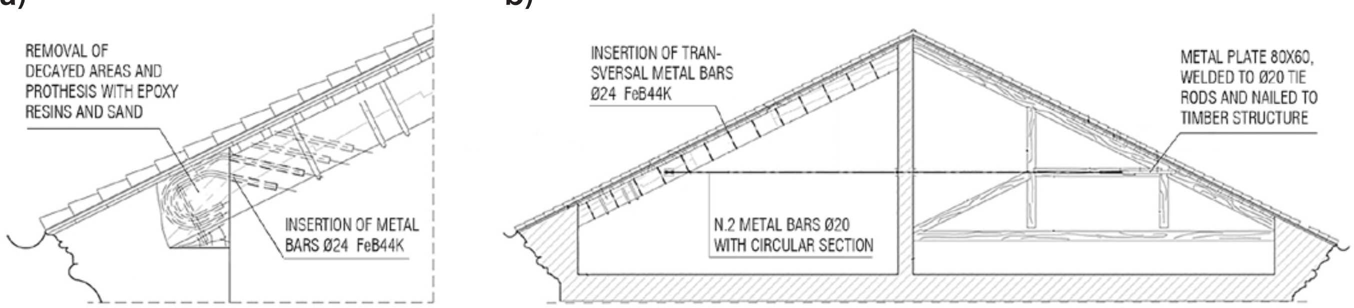

Fig. 2. *Strengthening of the E-S timber roof carried out in 1999: (a) replacement of decayed extremities with epoxy resins prosthesis reinforced with metal bars; (b) insertion of metal bars along "trave composta" and connection between rafters and central wall with metal tie-rods. (Image source: SBAP-FE-ADOC – Mezzadringegneria – FE-ADOC, Tav. 42, Pos. 2955).*

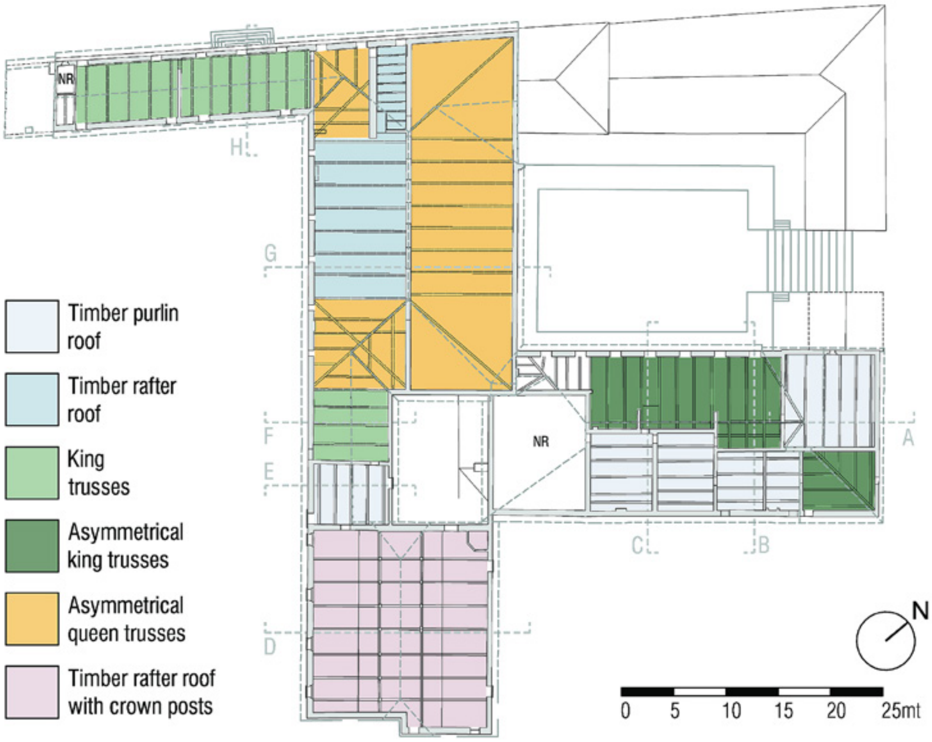

Fig. 3. *Site diagram of the timber roof with different types of timber structures.*

cross-section (17 cm x 50 cm), and the distance (175 cm) of purlins was increased. In this latter case, the technique of *trave composta* is used (Fig. 4a).

3.1.2. TIMBER RAFTER ROOF

The timber rafter roof is composed of beams with a length of 880 cm and a section of 17 cm x 50 cm, arranged perpendicularly to the ridge at a distance of about 220 cm. This type of roof is employed for the roof's southern pitch, and joists are parallel to the ridge. The technique of *trave composta* is used. Corbels are connected with the ends of rafters through u-shaped straps. Some extremities have been strengthened with epoxy resin prostheses or thick wooden boards with iron strips (Fig. 4b). As previously described, metal elements have been inserted, and double tie-rods connect the rafter with the central wall, probably replacing the previous wooden collars.

3.1.3. KING TRUSSES

This type of roof is employed for gable roof portions with small spans (550-750 cm), distanced about 170 cm. Joists are parallel to the ridge. Joints between the rafter and tie-beam were reinforced laterally with C-shaped metal elements connected with masonry. Some trusses are supported by a corbel, connected with the tie-beam by means of iron strips (Fig. 4c).

Fig. 4. *Timber roofs types: (a) large-span timber purlin roof built with the "trave composta" technique; (b) timber rafters roof made with the "trave composta" technique; (c) a small-span king trusses roof with reinforcement.*

3.1.4. ASYMMETRICAL KING TRUSSES

In the case of large-span pitches (680-880 cm), one of the rafters is extended up to the ridge. Moreover, in this case, the ridge is not aligned with the masonry walls, so the posts are off-centered with respect to the tie-beam. A secondary rafter is added to connect the tie-beam end to the extension of the opposite principal rafter. Larger span trusses were reinforced with metal props (Fig. 5a). The distance between trusses is about 170 cm, and the joists are parallel to the ridge. An asymmetrical king truss is also adopted for the N-E hip.

3.1.5. ASYMMETRICAL QUEEN TRUSSES

The queen truss, also called *alla palladiana*, composed of two posts, a tie-beam, a straining beam, and two symmetric rafters (going from the tie-beam and the straining beam), is employed here for large-span pitches (980 cm) but with a variation: an upper rafter is added to connect the straining beam to the ridge, whereas the opposite post is longer to meet the upper of the rafter. The trusses are connected to the central wall with two levels of metal tie-rods that connect, in turn, the rafters with a three-way strap (Fig. 5b). Note that the tie-beams support the timber ceiling of the great hall below, known as *Sala delle Carte Geografiche* (Geographical maps' room) richly decorated with squared coffers. Therefore, the decoration determines the distance between trusses (about 220 cm). Joists are parallel to the ridge. Asymmetrical queen trusses are also adopted for hips and intersections between perpendicular slopes (Fig. 5c).

3.1.6. TIMBER RAFTER ROOF WITH CROWN POSTS

The gabled roof of the southern area of the building consists of long and slender rafters that join the small king trusses towards the ridge area (Fig. 6a). The joint between them is obtained through a groove in the support, which guarantees both compression and traction resistance. Each truss rests on two crown posts by means of collar purlins composed of two beams connected with a particular scarf joint known as *dardo di Giove* (Fig. 6b). The central mezzanine is supported by tie beams that lay on two longitudinal wooden beams resting on pillars. The tie beams are located under the rafters but are not connected to them. The rafters and the tie-beams rely on the external masonry wall, to which they are connected with metal anchorages. Instead, the rafters are nailed to a 2-meter-long wooden corbel protected with a bitumen coating only on the eastern side. Despite the wide span (1,650 cm), the rafters' cross-section is only 15 cm x 30 cm, and the distance between them is about 220 cm. These elements are, therefore, significantly slender compared to the loads they bear (previous interventions added a reinforced concrete slab to the flat tiles layer). Therefore, all the rafters show severe bending and deformation since they were already undersized when the palace was built (Fig. 6c). This timber structure already underwent several strengthening interventions: wooden elements were installed to reinforce existing beams, metal elements (plates, strips, etc.) were inserted to improve the connections both between the beams and among them and the supporting masonry, a cross-bracing system, was added to increase the roof stiffness.

Fig. 5. *Timber roofs types: (a) asymmetrical king trusses; (b) asymmetrical queen trusses reinforced with flitch plates at the joints and a double layer of tie rods; (c) intersection between asymmetrical queen trusses.*

Fig. 6. *(a) Timber rafter roof with crown posts; (b) connection between collar purlins highlighted by the presence of a wooden capital; (c) previous reinforcement for excessive deformation.*

3.2. ON-SITE ASSESSMENT OF DAMAGED TIMBER ROOF

The survey on Palazzo Costabili's timber roof structure was first limited to essential features (geometrical configuration, technology, and general state of conservation) to identify the most critical points. A more detailed analysis was later carried out on the structures that showed significant degradation, more specifically on the timber roof of the southern building, which was the most hit by the 2012 earthquake. The structural seismic response of timber roofs to an earthquake is extremely interesting as it highlights weaknesses that do not appear with ordinary loads [5]. The excessive static deflection of the rafters worsened after the earthquake, and one showed bending cracks due to the vertical component of the seismic action. First aid interventions propped the structural element using metal supports (Fig. 7a). Still, masonry also presented severe crack patterns: vertical cracks in the corners reveal the activation of a tilting mechanism, whereas horizontal cracks in the upper area, all along the longitudinal walls, in correspondence of timber rafters and beams point to a slide of the upper part of the roof (Fig. 7b, c). Previous seismic reinforcements from the 1990s featuring reinforced concrete slabs, tie-rods, metal anchorages, and a bracing system, didn't do much against earthquake damage.

For this reason, further analyses were performed by specialists (Fig. 8a, b), who assessed the materials' consistency and the actual strength with a combination of visual inspection of timber features and defects (visual grading) and instrumental non-destructive measurements of physical-mechanical properties (mechanical grading), according to the UNI 1119:2004 standard [22]. The visual assessment was carried out on all physically accessible parts, whereas the less accessible areas (such as the ends of the beams inserted into supporting walls) were investigated employing alternative inspection methods (e.g., by resistance drilling methods) to define their state of conservation.

3.2.1. THE WOOD SPECIES IDENTIFICATION SYSTEM

The identification of wood species was performed by specialists visually and with laboratory tests (microscope analysis). For the main structural elements (rafters), wooden samples show that the wood used in the roof

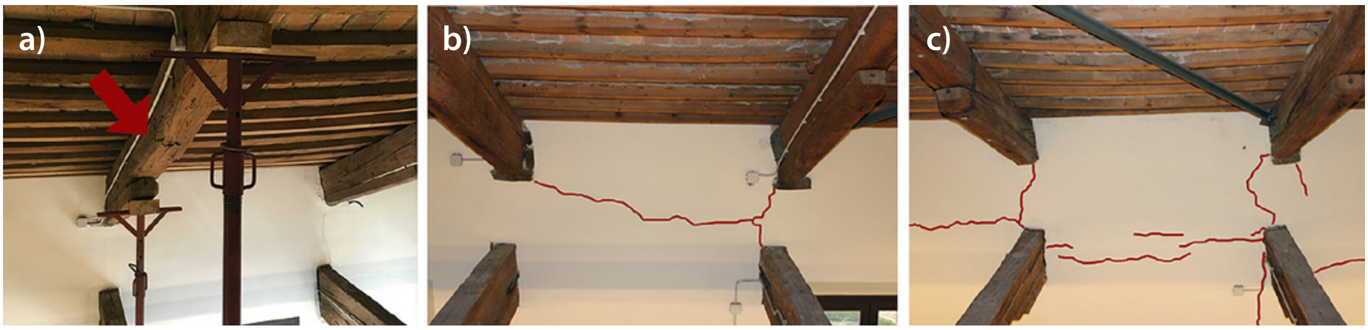

Fig. 7. *Seismic damages: (a) cracked rafter; (b, c) horizontal masonry cracks on longitudinal walls.*

structure is mainly Silver Fir (*Abies alba*) and Spruce (*Picea abies*), in line with the local construction tradition. Conifer was indeed the main species used in the timber structures of Ferrara's monumental buildings, whereas hardwood was mainly used for secondary elements. The use of fir is further proof of the importance that Palazzo Costabili might have had for the family since conifers do not grow locally, and their transport from the mountain regions was a costly practice [16].

3.2.2. WOOD MOISTURE CONTENT AND STATE OF PRESERVATION

The timber's moisture content was investigated with special instruments (drive in *Gann's electric hygrometer*), showing a percentage of humidity between 11-13%, a moisture level low enough to prevent biological and fungal attacks. No active decay or insect damage was detected. Previous deteriorations, such as fungus or xylophagous agents, were already found and solved in the past, as they are located only in previously consolidated timber members. However, the last restoration work removed the space between wood and masonry, preventing the aeration of beam ends and thus favoring moisture-due decay in case of water infiltrations.

3.2.3. EVALUATION OF MECHANICAL PROPERTIES

The assessment of the mechanical properties of timber was carried out by visual and mechanical grading. Non-destructive tests were performed with a drilling device (*IML Resi B-400 dynamometric drill®*) to define the effective (residual) cross-section. The investigation focused on the weakened parts, such as the extremities of the timber beams, close to masonry supports, which are also at higher risk of decay. The analysis found fibers with helical conformation and *cipollature* (ring shake) in several timber components, which is worrying as it compromises their earthquake and static strength performances. Finally, the mechanical properties were defined according to the classification of timber elements, based on wooden defects and decays, following the UNI 11119:2004 standard (Fig. 8c).

4. A STRENGTHENING PROPOSAL FOR STRUCTURAL SAFETY AND CULTURAL PRESERVATION

Inspection and assessments provided the data necessary to evaluate the roof's structural safety and plan potential restoration works that respect the minimal intervention principle and preserve original materials, structural systems, and techniques [4, 23]. An assessment of the areas that are most at risk and, therefore, a priority list for local interventions was defined [24], whose aim is to improve the structural safety of both the roof and the whole building.

Focusing on the southern building of Palazzo Costabili, a tie-rods system has been proposed to enhance the *masonry-box* behavior. This strengthening system,

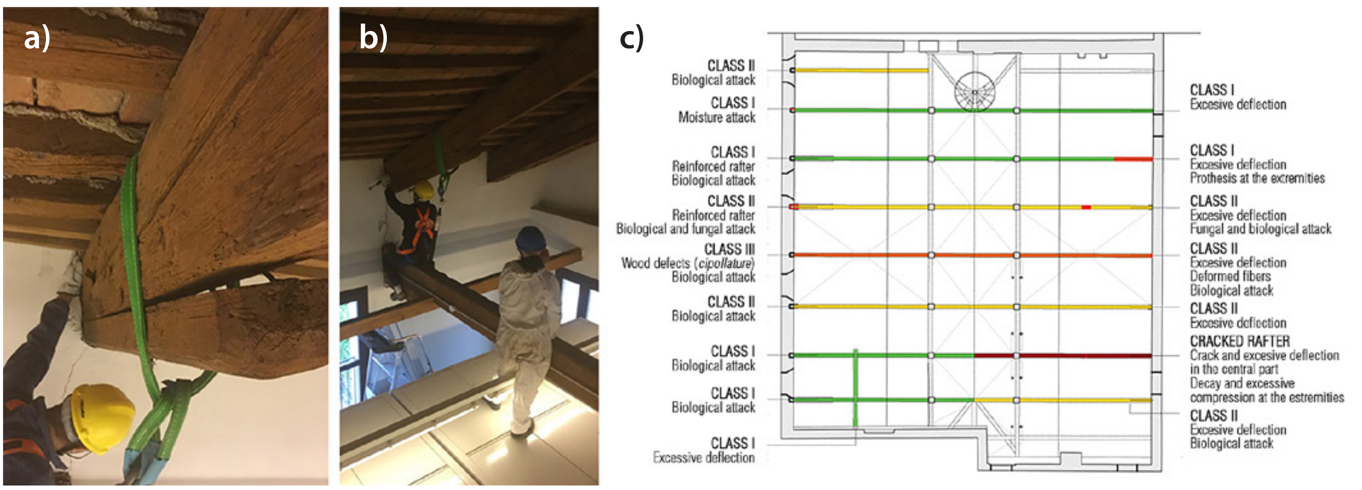

Fig. 8. *(a, b) The on-site assessment; (c) the classification of timber components with different colors (green class I, yellow class II, orange class III, red cracked rafter) according to their state of conservation (excessive deflection, biological attack, and wooden defects).*

connected to the roof structure, could transfer seismic shocks to the perimetral walls, thus preventing the upper part of the roof from sliding down. More specifically, two metal wires can be inserted in the central area of the building – the one most subject to tilting – in order to counter the roof's thrust and connect the lower parts of opposite rafters that are disjointed from horizontal wooden beams.

As per the timber structure, strengthening was calibrated explicitly according to the wooden structures' classification, state of conservation, and stress level. In particular, calculations to assess deformation were carried out to evaluate the real strength of the structure, and loads were surveyed in-situ to consider the structural resources of the existing construction. This analysis highlighted that the strength values of class I members are below the values prescribed by regulations for this kind of structure; therefore, no strengthening interventions were proposed. Class II and III elements showed reduced strength and suffered the most significant structural distress, as their stress values were above normal ranges. Urgent reinforcement is thus needed to avoid structural failure even with a slight increase in the bending stress (e.g., vertical seismic component), as already happened for one of class I or II elements. To preserve as much historical material as possible, the strengthening proposal of the original timber components suggests the addition of an intermediate support to transfer part of the static loads to the lateral supports with post-tensioned metal wires (Fig. 9). This active strengthening can be adjusted over time thanks to the calibration of the wires' tension utilizing telescopic props to guarantee durability. These elements also allow for reversing the deformation of the structure. The anchorage steel plate gives an additional contribution in balancing the inflection for intermediate support, located where the deformation is at its peak. This way, the number of metal surfaces in direct contact with timber could be reduced to a minimum to avoid moisture formation, which promotes surface decay. The only exception is the cracked timber rafter: in this case, the central plate should be enlarged to support the entire damaged area without replacing the original material.

Other interventions are required to improve roof stiffness. Indeed, despite the effectiveness of connections between members, the absence of efficient stiffening planking (the concrete slab over the flat tiles provided an inadequate seismic response in 2012) can cause problems in the case of earthquakes. A steel cross bracing was already inserted, but it is limited only to the central part of the roof, it is not connected to the perimetral walls, and it cannot homogenously transfer the seismic actions to transversal walls, avoiding the synchronous oscillation of the longitudinal ones. In order to enhance its effectiveness, the existing system (Fig. 10) should be completed with steel tubes with a circular hollow section, like the existing ones. The external span requires a specific bracing system because of shape and structural configuration irregularities. For this reason, at the edges, the cross-bracing consists of Ø32 mm metal bars connected to the timber structure in the upper part and the masonry walls at a lower level, in correspondence with the wooden beams of the mezzanine.

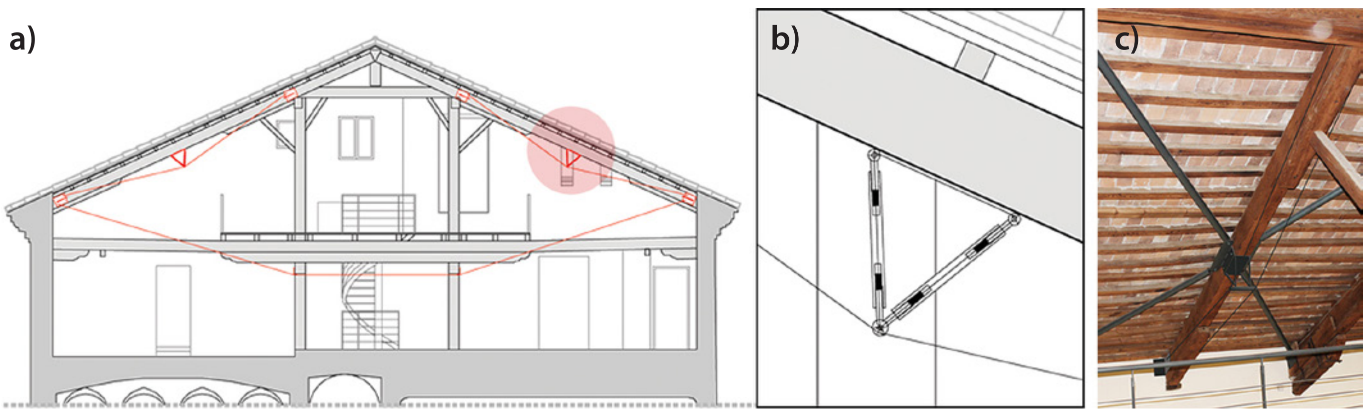

Fig. 9. *(a) A cross-section of the habitable attic room with the strengthening proposal for the roof structure. An intermediate support with post-tensioned metal wires has been added for class II and class III members: (b) a detail of the telescopic props; (c) a render of the reinforcement.*

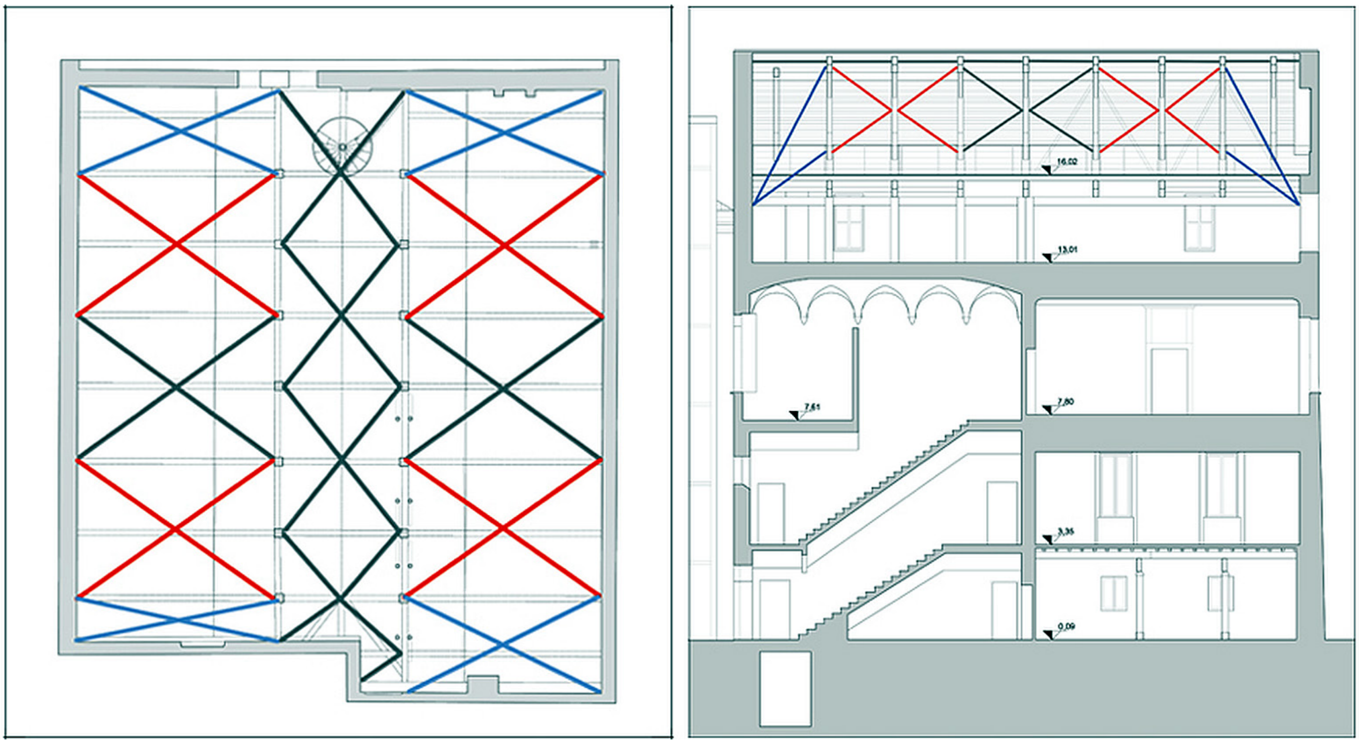

Fig. 10. *Improvement of the existing cross-bracing system of the southern timber roof: in grey are existing elements, in red is the new metal tube circular hollow section, while in blue are the new inclined metal bars.*

Finally, once the problems mentioned above have been solved, it is crucial to constantly control, monitor, and maintain timber structures considering the surrounding environment to minimize decay and subsequent interventions [25]. For the specific case of Palazzo Costabili, periodic direct visual surveys have been planned to assess possible modifications and identify the areas to be checked (bowing or leaning, cracking, wet areas, rot, decayed joints, etc.). Generally, such maintenance inspections should be carried out annually, but they are also needed after one-off events like earthquakes or storms. Moreover, since the current environmental conditions proved favorable for wooden preservation, temperature and humidity sensors should also be installed to detect possible alterations that may cause timber decay. Finally, maintenance activities (cleaning, minor repairs, etc.) should be defined accordingly to the result of regular inspections.

5. CONCLUSIONS

Interventions on historic timber roofs too often consist of widespread and excessively invasive reinforcements, if not in uncritical and complete replacement of the existing structures. This approach is due to the lack of critical knowledge-based analysis, recognition of the cultural value of existing timber structures, and poor understanding of their actual structural behavior (meaning residual mechanical performances and state of conservation). Situation and structural knowledge are thus essential to define strengthening interventions that preserve and reinforce historic timber roofs while preserving their cultural significance. The case study of Palazzo Costabili shows the importance of a critical knowledge-based approach to strengthening historical timber structures that considers the roof's features, its cultural value, and actual weaknesses.

This design of such a strengthening proposal both aims at increasing structural safety and preserving the authenticity of the historical construction. Issues such as compatibility, durability, and removability have been considered, as well as technical and structural requirements. An efficient balance between conservative and safety issues was sought, and strengthening has been precisely calibrated for each timber component. This was made possible by a knowledge-based method, considering the timber roofs' construction features and on-site assessments. It could be extremely useful in the future to preserve the original timber structure and improve its load-bearing function and the seismic behavior of the whole building.

In this regard, an interdisciplinary approach is fundamental: the cooperation between experts enables researchers to further analyze specific aspects, while coordination is key for a critical data analysis that provides a detailed state of the art of the structure object of the strengthening intervention.

Acknowledgments

The author acknowledges prof. Eva Coïsson for coordinating the study, the Suprintendence officers arch. Sardo and arch. Manara for managing the preservation activity and the CNR-IVALSA experts Nicola Macchioni, Elisa Pecoraro, Benedetto Pizzo for performing on-site assessment.

Funding

The study is part of a wider research aimed at studying the vulnerabilities of Palazzo Costabili for the definition of restoration and seismic improvement proposals, funded by the Regional Secretariat for Emilia-Romagna (MiBACT).

6. REFERENCES

[1] Bertolini Cestari C, 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 https://doi.org/10.1080/15583058.2018.1442523

[2] Cangi G (2012) Manuale del recupero strutturale antisismico. DEI Tipografia del Genio Civile, Roma

[3] LL.PP. Circolare n. 21745 (30/07/1981) Istruzioni per l'applicazione della normativa tecnica per la riparazione ed il rafforzamento degli edifici danneggiati dal sisma

[4] Cruz H, Yeomans D, Tsakanika E, Macchioni N, Jorissen A, Touza M, Mannucci M, Lourenço PB (2015) Guidelines for On-Site Assessment of Historic Timber Structures. International Journal of Architectural Heritage 9(3):277–289. https://doi.org/10.1080/15583058.2013.774070

[5] Zamperini E, Morandotti M (2013) Conservation of historic timber roofs: knowledge, monitoring, strengthening. Proceedings of 2nd conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

[6] Tampone G (1996) Il restauro delle strutture di legno. Hoepli, Milano

[7] Laner F (2011) Il restauro delle strutture di legno. Grafill, Palermo

[8] Giovannoni G (1936) Ferrara. The Palace of Ludovico il Moro. Rassegna di Architettura (8-9)

[9] Boari A (1914) Bramante, Rossetti e il Palazzo di Ludovico il Moro. In: Gazzetta Ferrarese. Officina della Gazzetta, Ferrara

[10] Marcianò AF (1991) L'Età di Biagio Rossetti. Rinascimenti di Casa d'Este. Gabriele Corbo Editore, Ferrara-Roma

[11] Alfieri N (1955) Il Palazzo detto di Ludovico il Moro. STER, Rovigo

[12] Calzecchi Onesti C (1936) Il Palazzo detto di Lodovico il Moro, Cenni Storici e Critici e Relazione sui Restauri. In: Aurigemma S (a cura di) Il Museo di Spina in Ferrara. Comune di Ferrara, Ferrara

[13] Di Francesco C (1996) Palazzo di Ludovico il Moro (Note Storiche). In: Atti del Corso di Aggiornamento "Giardini e Palazzi Rinascimentali di Ferrara. Sviluppo Urbanistico Moderno". Agea, Ferrara, pp 194–199

[14] Caglioti B (2021) Costabili Palace and the Architecture "all'antica" in Ferrara at the End of the XV Century. Athens Journal of Architecture 7:173–198. https://doi.org/10.30958/aja.7-0-3

[15] Zamperini E (2015) Timber trusses in Italy: the progressive prevailing of open-joint over closed joint trusses. In: Bowen B, Friedman D, Leslie T and Ochsendorf J (eds) Proceedings of the 5th International Congress on Construction History, vol. 3. Construction History Society of America, Chicago, pp 629–636

[16] Macchioni N, Fabbri R, Casali V, Crivellaro A (2004) Strutture lignee di copertura a Ferrara tra fine '400 e fine '600: analisi dei sistemi costruttivi, identificazione delle specie legnose e studio delle marche incise nel legno. In: Atti del workshop "Dalla conoscenza e dalla caratterizzazione dei materiali e degli elementi dell'edilizia storica in muratura ai provvedimenti compatibili di consolidamento". Politecnico di Milano, Milano, pp 209–224

[17] Giunchi E, Malvezzi R, Russo M (2002) Travi composte in legno nella Ferrara rinascimentale: indagini conoscitive e proposte d'intervento. Tesi di laurea, Università degli Studi di Ferrara, Facoltà di Architettura, rel. Alessandri C, Fabbri R, a.a. 2001/2002

[18] Barbagallo A, Bonora M, Marchi G (2004) Analisi degli schemi distributivi e strutturali degli edifici ferraresi di culto nei sec. XVXVIII. In: Fabbri R (a cura di) Ferrara Architettura 1. Edifici di culto, Ferrara, pp 9–32

[19] SBAP-RA-AFS (10/03/1992) Perizia n. 950 Registro unico delle misure

[20] MANFE ADOC (21/10/1993) Perizia n. 52 Lavori di sistemazione depositi nel sottotetto: registro unico

[21] SBAP-FE-ADOC – Mezzadringegneria – FE-ADOC, Tav. 25 (est) e 42 (sud) Pos. 2955

[22] UNI 11119 (2004) Cultural heritage - Wooden artefacts - Load-bearing structures - On-site inspections for the diagnosis of timber members

[23] ICOMOS – International Wood Committee (2017) Principles for the conservation of wooden built heritage. 19th General Assembly, Delhi (India)

[24] Coïsson E, Ferrari L, Manara S (2018) The Role of knowledge in defining strategies for conservation and strengthening: a case study from the 2012 Emilia earthquake. Proceedings of the 6th International Conference ReUSO "L'intreccio dei saperi per rispettare il passato, interpretare il presente, salvaguardare il futuro". Gangemi Editore, Roma, pp 1571–1582

[25] Della Torre S (2003) La conservazione programmata: una strategia per il patrimonio storico architettonico. In: Della Torre S (a cura di) La conservazione programmata del patrimonio storico architettonico. Guerrini, Milano