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

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

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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)

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LEARNING FROM TRADITION: A CASE STUDY OF THE DIAGNOSIS, DENDROCHRONOLOGICAL DATING, AND INTERVENTION ON A 16TH-CENTURY TIMBER ROOF STRUCTURE IN THE WESTERN ITALIAN ALPS

Tanja Marzi, Clara Bertolini-Cestari, Olivia Pignatelli

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Abstract

The paper presents a significant case study: the Church of San Giovanni Battista in Salbertrand dates back to the 16th century and constitutes one of the most interesting examples of religious architecture in the Susa Valley of the western Italian Alps.

Its historic timber roof structure was once at risk of demolition, but in 2000 finally became the object of necessary preservation and reinforcement works. Here, the interdisciplinary studies carried out for the diagnosis and assessment of the state of conservation are presented, starting with the identification of the wood species used, the geometrical survey, the visual and NDT diagnosis of the timber elements, and the structural evaluation. A special section is dedicated to the dendrochronological analysis, with a comparison of different case studies regarding larch roof structures of other historic architectures located in the northwest of Italy. The tree-ring sequences obtained from the buildings presented have also been used to define a larch chronology of the Susa Valley in Piedmont.

Following the first assessment phase, a second phase involved defining the restoration and reinforcement interventions. The reinterpretation of historic craftsmanship rules and traditions, which already contemplated the use of steel devices, attempted to offer alternative design solutions. This reinterpretation constituted the basis of the reinforcement interventions carried out in Salbertrand in the early 2000s. This paper highlights the importance of learning from historical treatises, showing how, even in modern reinforcement interventions, the application of traditional carpentry rules can achieve the aims of preservation and structural efficiency with overall cost-effectiveness and durability, resulting in a favorable balance between tradition and innovation.

Keywords

Architectural Heritage, Historic timber structures, Diagnosis, Dendrochronology, Construction Technology.

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1. INTRODUCTION

In building conservation, historic timber structures represent a specific class of handwork. They have particular importance and recognition due to their territorial diffusion, typological articulation, technological characteristics, and artistic and formal value. It is important to recall that these elements are built for structural purposes; however, especially in Italy, in the past, specific load-bearing timber structures in historic buildings did not receive the same attention and consideration than the buildings in which they are located. Therefore, they have not been treated with the same respect. Timber structures have often been demolished, replaced, or altered. Timber roof structures, in particular, have often met a worse fate than other structures because timber is a material that can easily be used, modified, or replaced in buildings. In the past, the neglect of these components was exacerbated due to the difficulty in assessing their actual condition and state of conservation of the historical timber elements and their mechanical performance, along with a lack of methodological pathways for the diagnostic phase.

Regarding their preservation, it was only recently that awareness was raised about restoring and preserving these structures as much as possible without altering their static role [1–3]. According to this idea, interventions should respect the nature of the structural elements and be coherent with their original conception and the material they are made of: wood. A major step forward in the diagnosis of wooden structures in Italy was taken with the definition of the standard UNI 11119:2004 *Cultural heritage - Wooden artifacts - Load-bearing structures - On-site inspections for the diagnosis of timber members* and of the standard UNI 11138:2004 *Cultural heritage - Wooden artifacts - Building load-bearing structures - Criteria for the preliminary assessment, design, and execution of works*, as well as other subsequent standards. Further advances in Italy have been made with the introduction of diagnosis as a mandatory phase within the tender procedure for works on historical roof structures.

In this context of intervention solutions, examining a few recent trends in the rehabilitation of wooden structures is interesting, with construction technologies that respect the guidelines recognized unanimously in the European context. These techniques make appropriate use of available resources in a perspective that tends to favor the concept of “sustainable technology” as a mediation between technological innovation, conservation, and the environment [4]. Special attention is paid to traditional intervention practices (such as replacing deteriorated elements with others made of wood or placing them side by side with other reinforcing elements such as wood or steel elements), as opposed to the use of more recent technologies (such as extensive use of reinforced concrete for the rehabilitation of timber floors, epoxy conglomerate prostheses for the heads of heavily decayed elements, fiberglass reinforcements, etc.).

Through the reinterpretation of historical treatises, this study intends to review traditional building methods to propose alternative design solutions to the repertoire of current intervention techniques. This operation does not mean a “return to the past”. Instead, it aims to take positive inspiration from the past to address a favorable convergence between tradition and innovation, between theory and practice, in compliance with the constraints imposed by economic assessments and needs relating to the sustainability of the built environment. Treatises and manuals of the 19th century are examined – a period in which there were many publications – and the focus is on works mainly referring to the western Alpine area in Italy. From these texts, general indications and specific suggestions proposed by the various authors on how to make interventions on timber structures have been analyzed. Particular attention has been paid to using metal elements to solve localized decay or reinforce the timber structure as a whole, restoring functional and structural efficiency to the wooden joints. Past suggestions, solutions, and rules, retrieved from the art of timber construction can still manifest aspects of excellent design interest today.

This paper analyses a significant case study: the church of San Giovanni Battista in Salbertrand, dating back to the 16th century and constituting one of the most interesting examples of religious architecture in the Susa Valley of the western Italian Alps. After risking demolition, its historic timber roof structure was the object of interdisciplinary studies carried out for the diagnosis and assessment of the state of conservation, involving geometrical surveys, the identification of wooden species, structural evaluation, visual and NDT diagnosis. A particular focus is placed on the dendrochronological analysis, which constitutes the basis for the construction of a larch chronology of the Susa Valley.

In the early 2000s, the reinterpretation of historic carpentry rules and traditions concerning, in particular, the use of steel devices attempted to offer alternative design solutions. It constituted the basis for the execution of the reinforcement interventions carried out in Salbertrand. The interventions on the church of Salbertrand forged a strict link between the preliminary diagnostic phase and the executive project (before the publication of the Italian standards for on-site inspections for the diagnosis of timber members). This approach was forward-looking and not particularly common at the time. The possibility of assessing the overall good state of conservation of these reinforcement interventions nowadays, some twenty years after they were carried out, constitutes an essential reference for future interventions. The long-term durability of these interventions and the need to preserve the original technological principles should be among the fundamental parameters of decision-making regarding the intervention techniques to be applied in structural rehabilitation projects.

2. LEARNING FROM TREATISES IN THE MAINTENANCE, REHABILITATION, AND REINFORCEMENT PROJECT

The construction techniques used in the past reflect a building tradition from which, despite the differences deriving from the various periods and geographical areas, emerges the importance attributed to maintenance work and how this is provided for in the design of a building. This relevance is proved by the historical treatises that contain many technical suggestions on the subject. In the past, maintenance, restoration, and renovation works were often carried out by modifying the existing building. Stone, wood, or metal elements taken from other abandoned buildings were often used. This recycling was achieved by dismantling and reassembling operations carried out by wise use of resources according to their limited availability [5, 6]. Maintenance works, therefore, were aimed at preserving the whole building through a continuity of transmission of traditional building techniques and with a program of interventions that allowed deteriorated elements to be replaced with sound ones.

Emy clearly expressed the concept of replaceability in one of the most precise carpentry treatises of the 19th century. In the *Traité de l'art de la charpenterie*, he suggests: «[…] if decay should be noted in any part of a construction, it must be quickly replaced with good materials […]» [7]. In the organization of the traditional building site, the replacement was an operation that was planned right from the design phase to ensure the easy replacement of a severely decayed part without having to pull down the entire structure. Owing to this ease of replacement, Emy states: «[…] and on this subject I will draw attention to the fact that joinery work that is very large in size, will be perfect and the cost of its construction well invested if, in addition to the conditions imposed by the purpose which has to be satisfied, it also presents the ease of replacing any of its parts which might show such deterioration as they might compromise the soundness of the building and the conservation of the other timbers […]» [7].

The undertaking of this program took place above all through the adequate design of the connections. Many treatise writers have emphasized the possibility of carrying out movements in the different directions of the wooden elements that converge in the joint. The wide range of connections they present required design criteria allowing easy replacement with simple temporary support of the structure.

Another important point about this maintenance system is the attention paid to the possible wood decay caused by biotic micro-organisms (fungi and insects). On this subject, in his manual *Technical elements in architecture* of 1924 [8], eng. Chevalley suggests that: «[…] when laying the roof beams, make sure they will last a long time by not closing them into the masonry (especially the heads of the tie-beams and rafters) so as not to risk the rapid decay of the structure». Along with these suggestions, Chevalley indicates two categories indicating how to position the heads of the beams so that they will last a long time: the first concerns the surface treatment of the head beams, and the second regards the construction technologies to insulate the wooden part from the masonry one.

Reinforcement work is intended to improve the structural performance of a building both in the design phase and in work carried out on specific parts. No matter if these latter have weakened due to phenomena connected with the characteristics of the material (rheological phenomena, movement of the geometry of the framework following cyclical settling of the wood) or on broken connections (caused by severe stress).

Reinforcements can be divided into two main groups: the first category concerns specific and localized parts of the structure (a connection or a section), which includes a series of devices such as bolts, arrow-head bolts, stirrups, brackets and metal laminas, and the second category that concerns the reinforcement of the whole structure or an overall increase in resistance and/or rigidity, such as reinforced beams which stand out for their originality of structural behavior.

2.1. METAL REINFORCEMENTS FOR LOCALIZED INTERVENTIONS

The use of metal elements as reinforcement of timber structures belongs to the tradition. Such practice has often been adopted in the past and may provide an effective way to increase strength and stiffness. Metal elements were used to compensate for the structural inefficiency of wooden components. Therefore tie-beams, strips, clamps, and metal connection elements were proposed to absorb traction stresses, improve faulty connections or restore missing ones. The new components were often placed alongside the original structure for structural collaboration.

The introduction of metal elements in the wooden structures to reinforce the connections took place, according to what the treatise sources testify, during the 19th century, with temporal differences between the different authors. In fact, we can note that, if in the 1830s Cavalieri di San Bertolo [9] considered it unnecessary to insert metal reinforcing, Breymann [10] on the other hand, towards the middle of the 19th century, deemed the exclusively wooden connections to be outdated, when he states: «For this purpose, a varied quantity of connections, partially very ingenious, was conceived […], since iron in the form of strips, screws, and similar, provides an excellent auxiliary element to add solidity combined with the simplicity of connection». Emy gives a synthetic but accurate picture of the gradual introduction of metal elements in wooden structures «[…] iron in timber construction is used in several circumstances to join pieces of timber together, to increase their strength, to consolidate the joints, to provide supports, to serve as an intermediate surface for wooden connections, and finally to replace a few pieces of wood. […] At first it was used to join different pieces together and to reinforce joints, and after a few years, during which the use of iron frameworks became frequent for roofs, attempts were made to use them as supports or tie rods for the timber framework» [7].

Emy's description on this point is also more satisfying as it is not limited to re-proposing pieces of advice drawn from the reading of previous authors. Still, he tries to deepen the reasons for the suggestion and to adopt it differently in response to specific problems, both in use for the reinforced beams and more in general in the connections (Fig. 1).

2.2. METAL REINFORCEMENTS FOR LARGE-SCALE ELEMENTS: REINFORCED BEAMS

This type of device refers at the beginning mainly to the supporting structures of the floors to obtain beams with greater resistance to deflection and thus contain deformations. In the evolution of these types, in the last quarter of the 19th century, reinforced beams were also used in roof structures (an example is the case of the Polonceau truss).

The system of reinforced beams became primarily widespread from the 17th-18th century. Jousse, whom Rondelet indicates as one of the first treatise writers on wooden carpentry, proposes in his *Le théâtre de l'art de charpentier* three examples of beams reinforced by different systems [11]. According to Rondelet these reinforcements that combined strength and economy were adopted «[…] because large-sized timbers are rare and very expensive, and generally of a less safe quality» [12]. Rondelet mentions this system as very frequent at the beginning of the 18th century, also used for the large halls of the Louvre. In its basic structure, the reinforced beam is made up of a wooden element of equal length to the span to be covered, over which two contrasting struts are positioned through different systems of jointing, indentations, bolts, and stirrups.

An effective system for stiffening very long beams, stressed in bending, was to provide them with other intermediate supports, through "columns" or struts, supported by tie rods that connect to both ends of the beam.

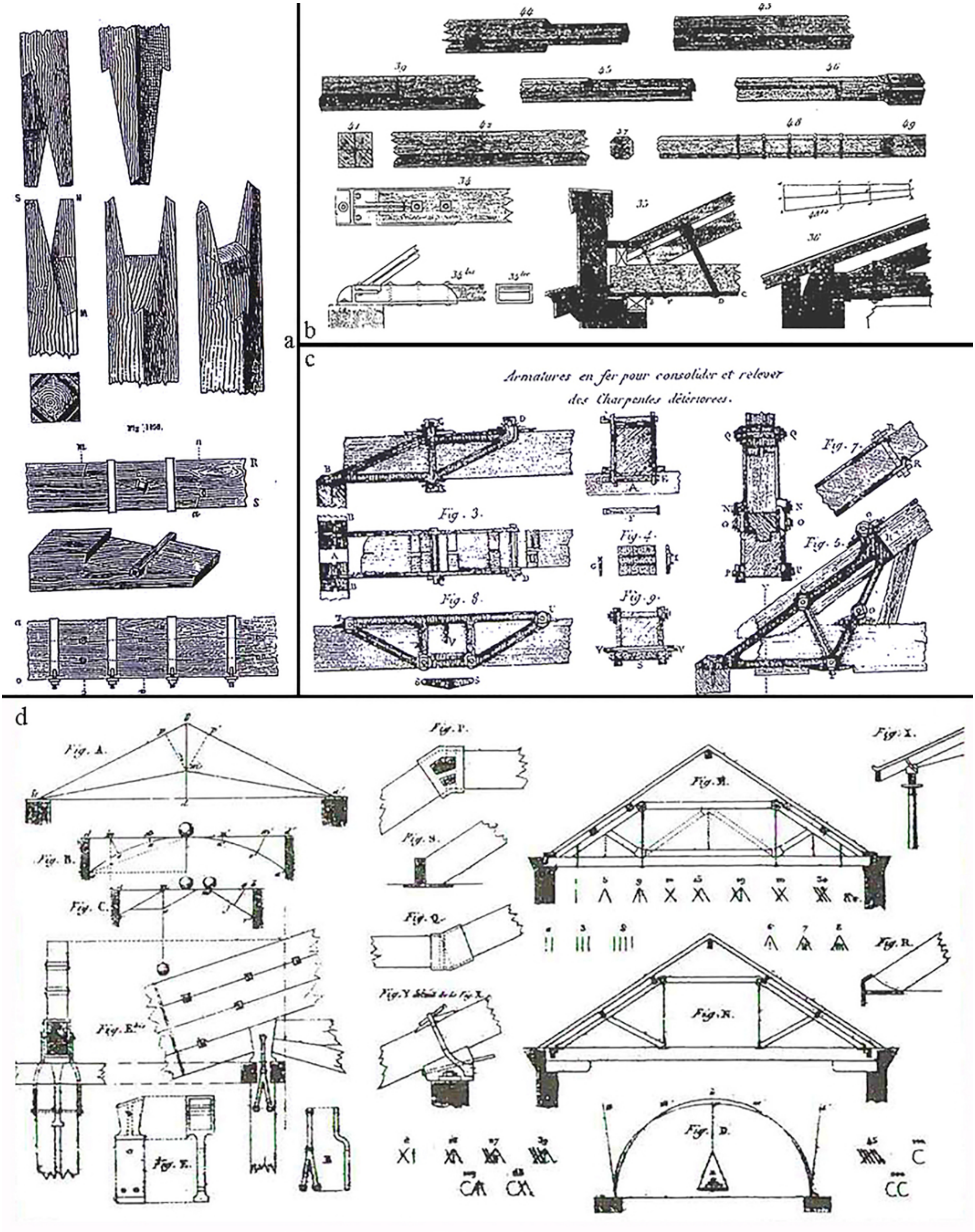

Fig. 1. *Joints timber/timber or with metal reinforcements for decayed elements, drawings from historical treatises and literature: (a) Pareto, Sacheri, 1880 [39, Vol. II, Part III, Cerriana S (ed) headword "Commessure", p 777]; (b) Emy, 1856 [7]; (c, d) Rondelet, 1802-1810 [12].*

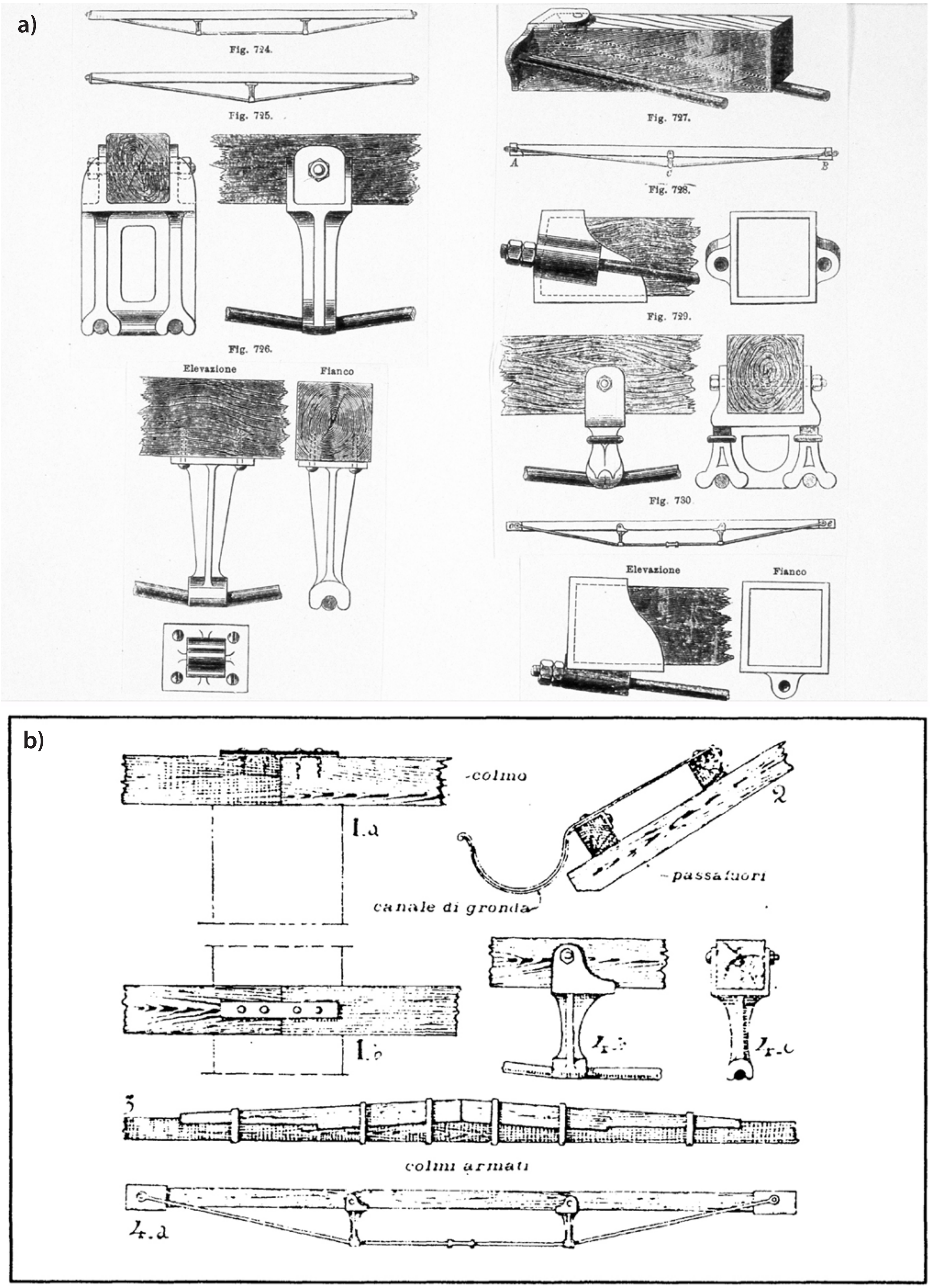

Fig. 2. *(a) Reinforced beams with one or two struts and details of the tie rods and struts in cast-iron, from Pareto, Sacheri, 1889 [39, Vol. VI, Part II-43, Cerriana S (ed) headword "Solai e soffitti", pp 330–331]; (b) reinforced ridge beams, from Chevalley, 1924 [8].*

Thus, were obtained the reinforced beams with one, two, and three struts. In all these typologies, the beam was made of wood, the struts of cast iron, and the tie rods of iron. Among the first solutions, the Polonceau truss [13] stands out for its maturity of conception and extraordinary correspondence between the geometric configuration and the tensional state of the elements. It was designed in 1837 for pitched roofs and was conceived as a mixed structure in wood, iron, and cast iron.

Different types have originated from the evolution of the older form of the reinforced beam described above, whose structural conception is of great appeal and simplicity. All types stemmed starting from the mid-19th century, in which the construction rationality, favored by developments in science and construction technique, tried to make the most of the materials used: the first reinforced beams were in wood, iron, and cast iron, then in wood and iron and finally all in steel (Fig. 2).

3. THE TIMBER ROOF STRUCTURE OF THE SAN GIOVANNI BATTISTA CHURCH IN SALBERTRAND

The municipality of Salbertrand, a small village located in the Susa Valley (Northwest of Italy close to the French border), still preserves its medieval architectural heritage almost intact, among which the parish church of San Giovanni Battista stands out, representing an important example of Gothic architecture. Alfredo D’Andrade referred expressly to some medieval architectures of Salbertrand in the construction of the “Medieval Village” built in Turin for the Turin Exposition of 1884.

Salbertrand is located over 1,000 meters above sea level, and most of the municipal land is covered by wooded areas. The largest site is represented by the *Gran Bosco di Salbertrand* Natural Park consisting of 3,775 hectares that develop on the orographic right side of the Susa Valley, from 1,000 meters to 2,600 meters of altitude, a mixed forest with magnificent specimens of silver fir, spruce and larch, quite unique in the landscape of the Alps of the Piedmont region (Fig. 3). The forest has represented for centuries the economic driving force of the Salbertrand community, differentiating it from neighboring villages mainly for quantitative terms and the high quality of the trees [14]. This high quality was already well known in past centuries. The large wooden beams coming from the Gran Bosco have allowed, starting from the 17th century, the construction of some of the most important military and civil engineering works as well as important architectures of Turin, the Savoy capital. Among them, we can count the Basilica of Superga, the royal hunting palace of Stupinigi, the Regio Theatre, and the Valentino Castle [15].

In recent years Salbertrand has been at the center of a large project supported by the European Union of enhancement and rehabilitation, with specific interven-

Fig. 3. *(a) Historical map of forests around Salbertrand (Mappa dei Boschi di Exilles, 1739, from [14]); (b) view of the larch trees in the Gran Bosco di Salbertrand Natural Park; (c) view of the village of Salbertrand with the Gran Bosco on the background. (Image source: photos courtesy of Gran Bosco di Salbertrand Natural Park).*

Fig. 4. *Church of San Giovanni Battista in Salbertrand. External church views. (Image source: photos courtesy of Gran Bosco di Salbertrand Natural Park).*

tions aimed at conserving the cultural heritage of the historic villages of the Susa valley.

Among its most important buildings is the church of San Giovanni Battista, built between the 12th and 16th centuries. It constitutes one of the most interesting examples of religious architecture of the Susa Valley, a monument of significant interest under the architectural and construction profile. The church was originally a Romanesque building oriented towards the east, of which only the lower part of the bell tower has been preserved up to the present day (Fig. 4).

The first document in which the church is mentioned dates back to 1057. Rearranged in the following centuries, the church underwent an almost total reconstruction during the 16th century. After this intervention, it did not undergo significant changes, and it is still one of the best-preserved and richest examples of late Gothic Alpine churches. The building faces west on the churchyard with a monumental entrance porch, supported by two monolithic octagonal pillars that bear the date of construction: 1536. The interior has three naves separated by simple and multiple columns and complex Gothic pillars on which the capitals lay, diversified from each other on a stylistic and iconographic level. The wider and considerably higher central nave ends in a presbytery where the main altar is located.

Among the numerous architectural values of the church, such as the entrance porch, the portals, the columns with sculpted capitals, frescoes, etc., the covering of the central nave, which can be defined as a “gabled” roof with two inclined pitches, constitutes a masterful example of wooden carpentry of the 16th century [16].

The roofs of the church are organized on different levels and consist of: the roof of the bell tower, the main roof covering the central nave, the two lower-level roofs that cover the side aisles, the roof of the sacristy, the roof of the side chapel on the right of the main altar and the roof of the entrance porch.

All roofs are characterized by the following:

- the main structure in larch wood;
- a natural split stone slate roof covering;
- thick larch planks that support the stone slates.

The pitched roof of the central nave – the object of the present study – has two slopes with a sloping angle of 29°. It is composed of three small timber trusses of about 8 meters of span on which a large ridge of 20 meters (with a diameter of about 50 cm) supports 13 false rafters on each side of the slope displayed at close distance (Fig. 5).

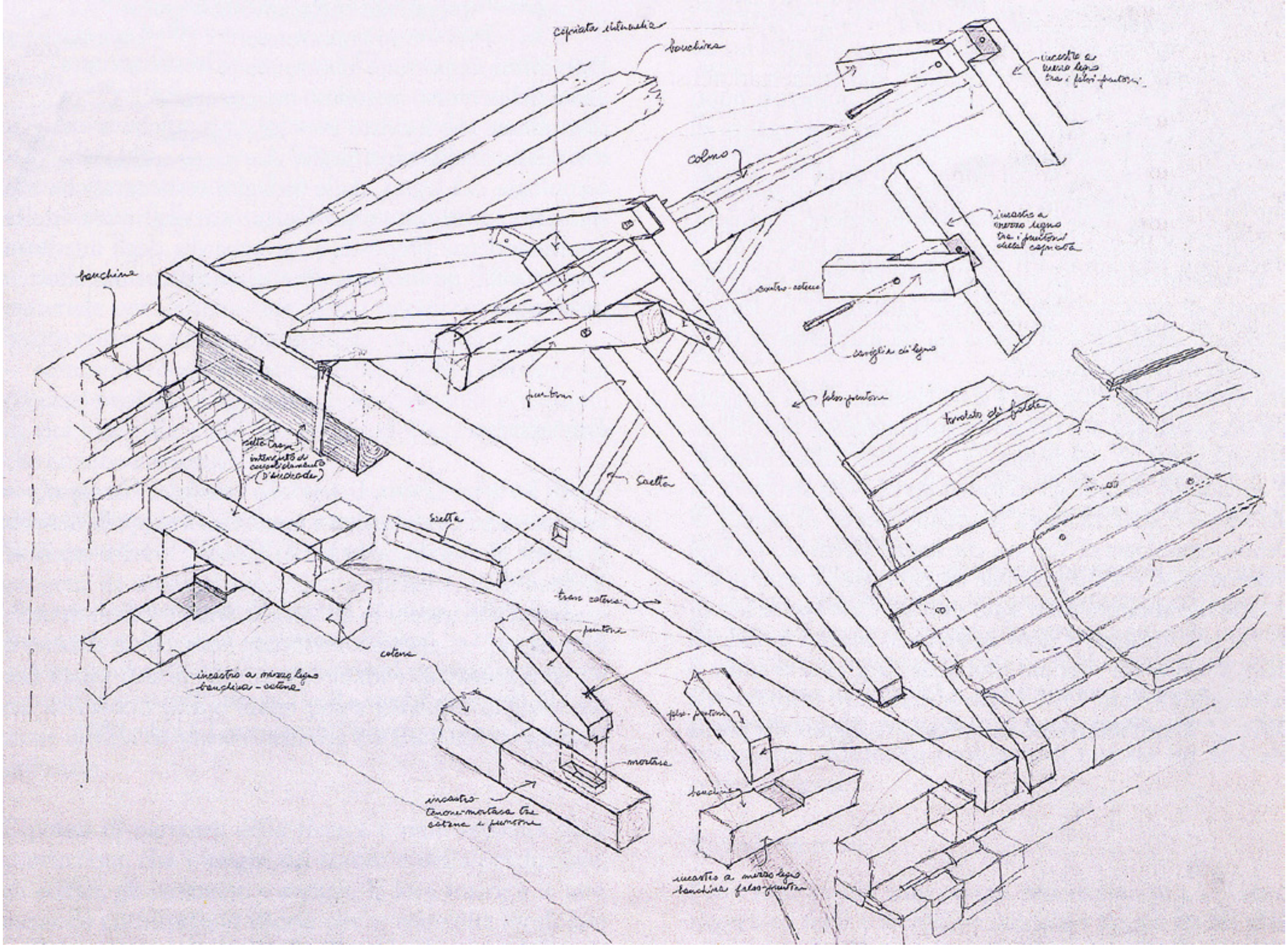

Fig. 5. *Church of San Giovanni Battista in Salbertrand. Construction survey of the timber roof structure and the typical wooden joints. (Image source: drawings courtesy by C. Bertolini-Cestari).*

The specificity of the trusses is the position of the connection between the tie-beam and the rafters, which is set back from the joint between the tie-beam and the longitudinal masonry walls of the central nave. This condition leads to part of the element being subject not only to tension but also to bending. With this arrangement, the ridge assumes a fundamental role in preserving and conserving all the different elements constituting the roof, particularly the inclined elements defined as false rafters. However, the roof structure, which appears poorly braced in the longitudinal direction, is connected on the slopes with two horizontal beams resting on the masonry walls.

The roof covering is realized with split local stones, also called "*lose*", large slates typical of the area fixed with dowels to the wooden boards that rest on the false rafter. Most of the wooden carpentry is in larch (*Larix decidua* Mill.) from the nearby Natural Park of the Gran Bosco of Salbertrand.

On the one hand, carpentry is characterized by skilled and valuable woodworking of the elements and joints. The connections between the rafters are half-timber with wooden dowels, those between the rafters and the tie-beam are tenon and mortise, as well as those between the false rafters in the support on the ridge and on the side platforms. On the other hand, the roof is characterized by the exceptional size of the ridge; a large beam of over 20 m long with an average diameter of 48 cm, which rests on the three trusses. Therefore, realized with a very durable material (larch) and of excellent quality, the carpentry had not undergone substantial restoration over the centuries, except for a reinforcement of a head of the tie-beam of the central truss. This intervention presumably dates to the end of the 19th century, when Alfredo D'Andrade was in charge of the regional office for the conservation of the monuments of the regions of Piedmont and Liguria [16, 1].

4. DIAGNOSIS AND ASSESSMENT OF THE TIMBER ROOF STRUCTURE OF THE CHURCH OF SALBERTRAND

The case of the roof of the parish church of San Giovanni Battista in Salbertrand represents an emblematic example of how a proper diagnosis and assessment of the timber structure constitutes an essential basis for its preservation, being able to avoid unnecessary dismantling or loss of the original wooden carpentry. The research carried out by the Department of Architecture and Design of Politecnico di Torino, in agreement with the National Board of Antiquities, was focused on the preliminary investigations (carried out in the late 1990s) and the project of rehabilitation of the timber structures (carried out in the early 2000s) with reinforcement interventions to allow the maximum preservation of the original elements. A qualifying aspect of the methodological path was the multi-disciplinary activity that has involved various professional figures from different sectors, such as architects, civil engineers, wood technologists, historians, and dendrochronologists, with the supervision of the National Boards of Antiquities responsible for safeguarding structural interventions on buildings belonging to our historical-environmental-cultural heritage.

The diagnostic and assessment phase was focused on the following:

- historical analysis and archival research on the documentary historical sources of the origin of the church and of the successive interventions over time;
- geometrical survey of the structures;
- identification of wood species and their characteristics;
- assessment of the state of conservation of wood material: visual inspections;
- assessment on the state of conservation of wood material: instrumental analysis;
- a further study phase was conducted to date the most important wooden elements through the dendrochronological survey. In view of the intervention, it was considered essential to have a sufficiently reliable dating reference of all the wooden elements of the structure (this investigation is described more in detail in the following section 5).

4.1. IDENTIFICATION OF WOOD SPECIES AND THEIR CHARACTERISTICS

The identification was carried out in collaboration with wood technologists. It was partly carried out visually for the elements with evident characters on the visible parts. In case of doubts, wooden samples were taken and identified in the laboratory with microscope analysis.

The tests that were carried out (macroscopic and microscopic) on the main elements of the roof system have provided the following results:

- the wooden elements constituting the main structure, the trusses (rafters, tie-beams), the ridge, the horizontal beams, the false rafters, and the planks appear as original elements and in larch (*Larix decidua* Mill.);
- some secondary elements, such as the connecting elements, belong to other wood species. The sampling of these elements was also limited to avoid damaging them excessively. For example, the wooden dowels of the rafter joints of the trusses and those of the "*lose*" stone slates are made of laburnum (*Laburnum anagyroides* Medic.). While the bracket, which supports one end of the tie-beam of the central truss, is made of oak (*Quercus petraea* Liebl.), etc.

Larch generally has heartwood resistant to alterations by fungi, while the sapwood is less durable. As regards the attacks of the most common xylophagous insects, this species does not appear to be of high resistance. Attacks by fungi or insects result from prolonged high moisture levels [17]. Also, in this case, due to the lack of portions of roof covering slates, in correspondence with some parts exposed to repeated infiltrations of rainwater, degenerative phenomena occurred in the wood. The knowledge of the specific characteristics of the wood species used in a structure proved once again to be indispensable for a thorough diagnostic study.

4.2. GEOMETRICAL SURVEY

The diagnostic activity involved a preliminary phase during which, simultaneously with the historical analysis, general data collection was carried out on the main geometric characteristics and the construction technology of the roof. Therefore, understanding the structure passed through an accurate geometric and photographic survey.

For the geometric survey, the technique used and the measurements carried out were very detailed as it was necessary to provide indications also on the different types of connections, on the interventions carried out over time, and on the additions, deformations, and decays of the various elements and of the ridge beam in particular. The survey was developed through plans and sections and carried out with traditional techniques. It was also due to the difficulty of accessing under the roof with bulky instruments, as they were at that time. An accurate geometrical survey of the structures, with details of carpentry and joints, has been carried out with drawings in scale 1:50, 1:20, and up to 1:5 for the construction details. The graphical drawings constituted the basis of the instrumental investigations for assessing the decay and state of conservation.

4.3. VISUAL INSPECTIONS

Visual inspections were carried out following an inspection protocol defined by the experience carried out by the same multi-disciplinary research group on the great trusses of the Valentino Castle in Turin. The visual inspection aimed to evaluate the original characteristics of each wooden element and the variations undergone during the structure's service life.

The visual inspection was systematically conducted on all parts of the roof structure (elements and their connections). It led to an initial evaluation of the defects and macroscopic characteristics of the wood, such as: the direction of the grain, the depth, and direction of the cracks, the different colors between sapwood and heartwood, the chromatic alterations due to fungal and xylophagous insect attacks. The determination of the depth and direction of the cracks was carried out with special harmonic steel blades. This survey could also detect the eventual presence and extent of ring-shakes (not present in this case).

As for the ridge beam, it was observed that it is made of a single larch wood element of considerable size and high regularity of shape. The tree trunk areas from which the timber element was obtained have been identified for this beam. In the area close to the facade, both the form of the pentagonal cross-section and its greater diameter reveal that this is the trunk basal part, which presents a higher extension of heartwood. On the other hand, the more regular, cylindrical section towards the apse identifies the trunk's top part. Technological observation, therefore, assumed great importance in obtaining information on the mechanical characteristics and durability of the material.

4.4. INSTRUMENTAL ANALYSIS

The visual inspection was integrated with NDT instrumental inspection. At first, wood moisture content was determined through a portable resistance-type electrical moisture meter. The knowledge of wood moisture content is crucial because it is a limiting factor for the development of fungi and wood-boring insects able to damage the wood. This first instrumental analysis (on the first level), carried out in the dry summer period, gave very variable humidity values along the ridge beam. The average values measured were: 12-13% in healthy areas and generally in the basal part of the trunk; 25% in areas colonized by active fungal mycelia; 17-18% in the areas damaged and affected by the decay of the wood due to brown-rot.

Afterward, visual inspection was integrated with instrumental tests to measure the wood's resistance. At the time (the late 1990s), two portable micro-drilling instruments/resistance drilling were mainly used: Resis-

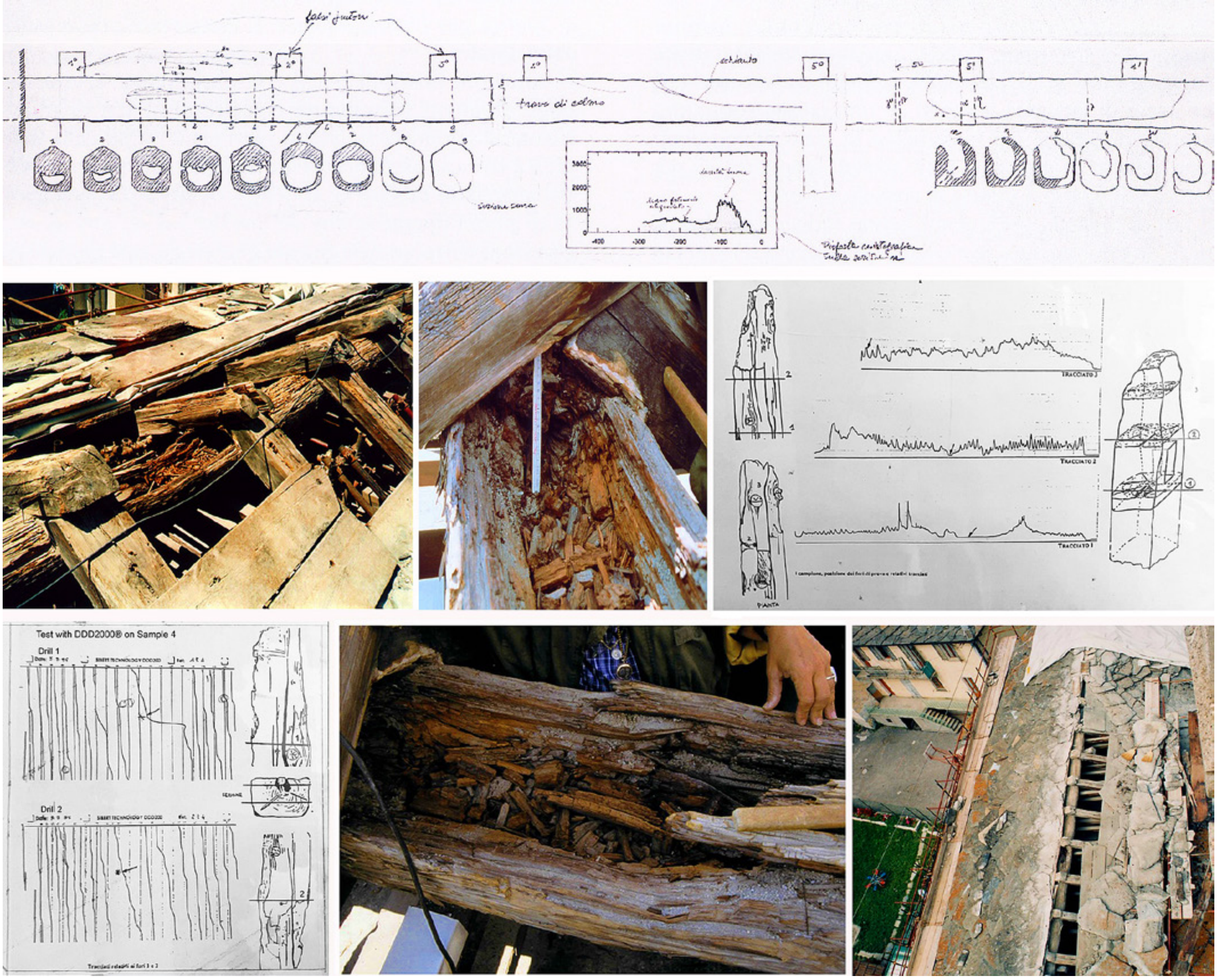

Fig. 6. *Church of San Giovanni Battista in Salbertrand. Geometrical survey with indications on the state of conservation of the ridge beam (decayed and sound beam sections). Examples of resistance drilling graph (Resistograph® and DDD2000® tests) and corresponding test points/ directions; Photos of the decay detected on the ridge beam. (Image source: drawings and photos courtesy of C. Bertolini-Cestari).*

tograph® and DDD2000®. Such instruments allow the evaluation and quantification of the decay of the timber elements enclosed inside the masonry. In fact, this type of non-destructive test completed the visual survey to detect alterations that are not visible on the timber member's surface but may be inside (Fig. 6).

At first, some tests were carried out with a Resistograph® instrument, which evaluates the density of the wood through the resistance that the wood itself opposes to the penetration of a very thin drill (which produces a 3 mm diameter hole). This survey generates graphs showing: the depth of the hole to a 1:1 scale along the abscissae axis and the resistance to penetration along the ordinate axis, expressed in the amplitude of both the wooden rings' mechanical resistance and the moisture levels of the wood. Somehow similar is the DDD2000® (Decay Detecting Drill), a drill that makes a hole of only 1.7 mm in diameter. In this case, the drill speed is not kept constant, but the data recording is based on its variation. Tests were carried out on sections affected by the ridge beam's degradation. Tests with DDD2000®, in a total number of 31, were performed radially with respect to the longitudinal axis of the ridge beam. Tests with Resistograph®, in a total number of 21, were performed radially with respect to the longitudinal axis of the ridge beam. In the areas with severe decay, a complete correspondence was found between the results of the Resistograph® and those of the DDD2000®.

Another type of survey that was used, which was not localized or destructive, was the one involving the use of ultrasound instruments (Silvatest®). In this case, the use of electronic equipment allowed the estimation of the mechanical characteristics of the elements investigated. In the tests carried out in Salbertrand, the piezoelectric transducers at 55 kHz were used both transversely and diagonally to the wood. Here, too, the aim was to detect the presence of defects and decay within the wooden artifacts and to locate their position with precision. The limit of this equipment depended on the unlikely probability that the two heads of the timber component would be free. Consequently, ultrasonic assessments conducted on only one side of each element resulted in the variability of the measurement that made them ineffective in the evaluation of mechanical resistance.

4.5. RESULTS OF THE ASSESSMENT ON THE STATE OF CONSERVATION OF WOOD MATERIAL

The different levels of on-site investigation – visual and instrumental – allowed the characterization of the material and the evaluation of the state of preservation of the timber elements [16, 18] and proved to be fundamental for the study of possible reinforcement hypotheses.

Preliminary investigations identified several types of decay, whose main causes can be summarized as follows:

- abundant water leaking caused by the decay on the covering stone slates brought to the presence of xylophagous insects with extensive demolition of the cellular part of the wood (cavities and rot) and subsequent reductions of the resistant sections up to 1/3 of the original section for a total length of 6 m (Fig. 6);
- deformations and twisting from the shrinkage in the head connections of the false rafters, caused by slight structural failures of the ridge beam and by the decay of the contact surfaces.

The inspections carried out in the late 1990s showed an overall good state of conservation of the trusses and the rafters. Still, there was a severe biotic decay of the ridge beam in two areas (4 m length on the apse side and 2 m towards the façade side) (Fig. 6). Furthermore, due to creep (or *fluage*) in these areas of the ridge beam, a substantial deformation of about 30 cm at midspan appeared.

This state of decay and degradation required an urgent reinforcement intervention, considering the snow loads, which are abundant in the mountain area, and the great weight of the roof covering in stone slates.

From the analysis of the results obtained from the surveys, the following documents were prepared, constituting a fundamental basis for the study of possible reinforcement hypotheses:

- thematic charts, based on the construction-geometric surveys which highlighted: identified wood species; material defects; the presence of shrinkage creeks; decay, rot, cavities due to xylophagous agents; disconnections of the joints caused by deformations, shrinkage or partial collapse, etc.;
- first structural modeling of the behavior of the system as a whole;
- hypotheses for the integration and rehabilitation of the damaged parts;
- possible structural reinforcement solutions of the elements strongly compromised by the decay, based on those suggestions provided by historical treatises, particularly mindful of the conservation of the original wooden artifact: ancient suggestions and indications of operational practices that, necessarily updated, could effectively guide the rehabilitation intervention.

5. DENDROCHRONOLOGICAL SURVEY: A COMPARISON OF LARCH IN THE WESTERN ALPS FOR A REFERENCE CHRONOLOGY

Dendrochronology contributes to the knowledge of historical wooden structures, making it possible to date, sometimes with extreme precision, the wood assortments used in buildings. In Italy, dendrochronology is increasingly used in studying historical architecture, even if still not systematically, as in other countries such as Germany and Switzerland. In these countries, it is part of the preliminary diagnostic investigations for the rehabilitation project of a building, and the relationship between these investigations and the project is indeed very close. The publication of the Italian standard UNI 11141:2004 on *Dendrochronological dating guidelines* demonstrates the increasing interest in this discipline achieved in Italy.

The dendrochronological methodology is based on the principle that, in temperate zones, trees of the same wood species, which grow in the same geographical area, give rise in the same period to similar tree-ring series, where each ring corresponds to a calendar year. Therefore, the dating of an artifact of unknown age is obtained by comparing the tree-ring sequence that characterizes it with a reference chronology, representing the growth behavior of the wood species under examination over the centuries in that specific region. Therefore, of extreme importance research is the creation of reference chronologies for different geographical areas and species, which, in addition to increasing the chances of successful dating, also allows for identifying the probable site of origin of the wood used.

The studies conducted by the research group on the church of San Giovanni Battista in Salbertrand and other buildings in Piedmont, including in particular the Valentino Castle, represent interesting examples of the potential of the dendrochronological method, as well as constituting a valuable database for the construction of a reference chronology in this geographical area. Larch, the species used in the examined wooden structures, is widely used in the historical buildings of northern Italy [19–21].

In the presented case studies, an attempt has been made to select elements that preserved at least part of the sapwood and were characterized by a high number of rings. Since the beams were still in place, cores with a diameter of about 0.5 cm were extracted using a Pressler's increment borer. The sampling was always performed starting from the external edge towards the axial center, along two different directions, if possible, considering that a different number of rings could have been removed in the squaring of the beam. Only in some cases it was possible to take a cross-section of a few centimeters. The dendrochronological investigations were carried out following the classic procedures [22–24]. For the dating of the elements, in the absence of local reference chronologies, the chronology of the larch from the Vanoise Park (France) [25] was used since it referred to an area close to Valle di Susa and the possible provenance areas of the wood [15]. Subsequently, comparisons were also made with a chronology under development based on samples taken from living larch trees over five hundred years old from the Alta Valle di Susa (Pignatelli, unpublished data).

The Valentino Castle of Turin (Savoy residence of the early 17th century and Unesco World Heritage Site) represents one of the first dendrochronological studies conducted in Italy on wooden roof structures where extensive sampling was carried out [26, 1]. The investigations, which date back to the early 1990s, involved over sixty wooden elements belonging to the central roof and the four towers of the building. Thanks to the high number of wooden pieces examined and the presence of sapwood on 16 of the dated samples, it was possible to highlight the presence of different construction periods [26]. The oldest wooden elements are those belonging to the central roof, referable to the first phase of construction of the castle, documented by historical sources around 1620, while the beams of the roof structure of the towers belong to the years around 1630 (Fig. 7).

In the church of San Giovanni Battista in Salbertrand, the dendrochronological investigation was carried out on 13 elements of the timber roof structure of the church (truss beams, struts, false rafters, and planks of the roof), including a single plank attributable to the 19th-century restoration carried out by Alfredo D'Andrade, and on the ridge beam of the roof of the porch. The beams, not so accurately squared, allowed the conservation of at least part of the sapwood in most of the elements sampled, and in some cases, even the last ring under the bark seems to be present, allowing a precise dating (Fig. 8).

The dendrochronological investigations made it possible to date all the examined elements, dating back to

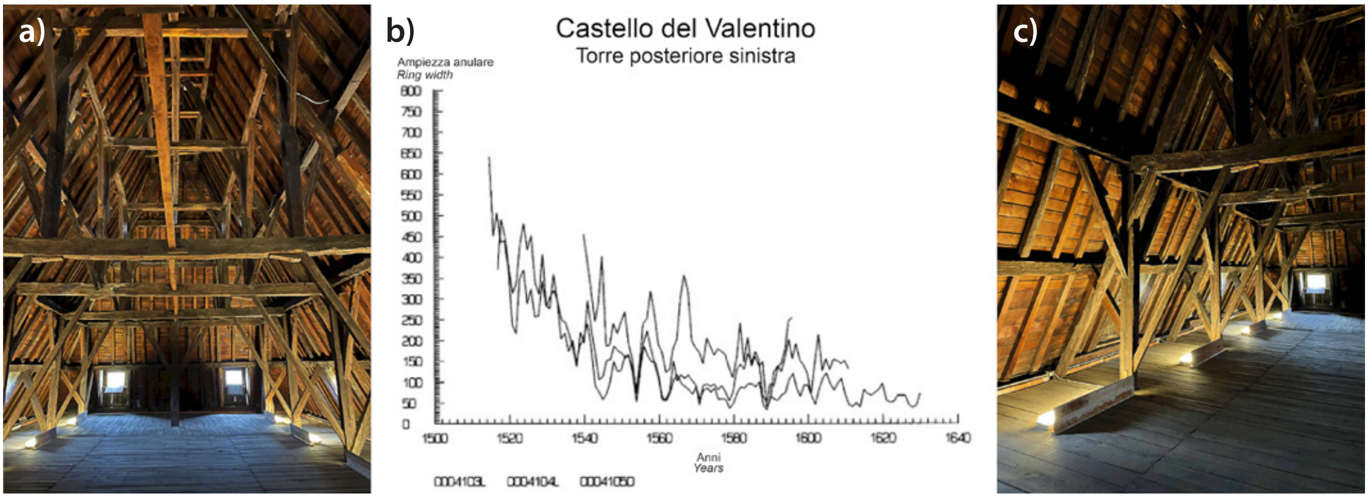

Fig. 7. *Valentino Castle, Turin: (a, c) view of the roof structures of the north-east tower (photos T. Marzi, 2022). (b) Dendrochronological curve of the three trusses of the back tower: the years, corresponding to the succession of the rings measured, are shown on abscissae, while the corresponding ring width is shown on the axis of ordinates.*

the 16th century, excluding the undated restoration plank. The chronology mentioned above of the larch of the Vanoise Park (France) was used for the dating. Comparisons were also made with the chronology elaborated for the samples of the Valentino Castle and the already mentioned chronology of the Alta Valle di Susa. The dendrochronological characteristics of the sequences suggest that the elements considered were obtained from larches probably coming from the same forest and referable to the same falling phase. By calculating the missing sapwood rings, it was possible to place the year in which the felling of the matrix trees may have occurred between AD 1513 and AD 1517. The probable presence in two samples of the cambium terminal ring (the so-called *Waldkante*), consisting only of spring wood, allowed hypothesizing that the felling of the matrix trees used for the roof took place at the end of spring and early summer of the year AD 1513 (Fig. 8). The result obtained for the ridge beam of the porch, whose last ring dated to the year AD 1520, constitutes the *terminus ante quem non* for felling, is in accordance with the date (1536) reported on the column of this part of the building.

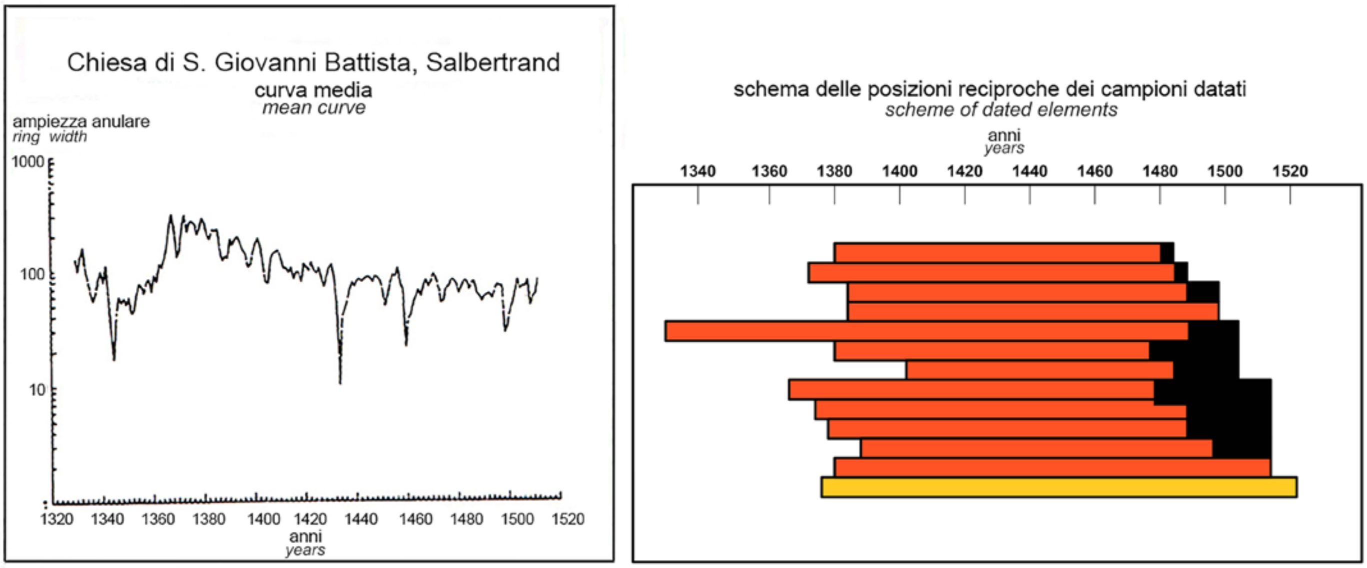

Fig. 8. *Church of Salbertrand. Dendrochronological mean curve. Bar diagram of the dated elements: in black, the part of the existing sap; in red, different samples from the timber roof structure of the church; in yellow, the sample from the ridge beam of the porch roof.*

The mean curve built for the roof covers the period between AD 1330 and AD 1512, overlapping only for a short time with that of the Valentino Castle (AD 1447-AD 1637).

Of consistent interest are the results obtained by comparing the mean curve of the Valentino Castle with the series obtained for the ridge beam of another small church, the Cappella del Seu, located in the Gran Bosco of Salbertrand, which covers the period AD 1490-AD 1674.

In particular, the optical and statistical high agreement (with t_{BP} higher than 8) between this last dendrochronological series and the Valentino Castle curve suggests that the wood used in the castle construction may have come from the woods of Gran Bosco of Salbertrand, as reported in some historical documents. This research results, obtained with extensive sampling, made it possible the dating the wooden structures examined and have become a fundamental part of the database created for the construction of a local chronology of the larch for the western sector of the Alps, from the 14th century to the present day. The systematic investigation of other historical buildings and larch forests in the Valle di Susa will allow the chronology to be consolidated and completed by improving the database relating to the valley.

6. THE SUGGESTIONS OF THE TREATISES IN THE REINFORCEMENT INTERVENTIONS OF THE CHURCH OF SALBERTRAND

A first intervention project, drawn up by the municipal technical office, was oriented towards replacing the ridge beam. But this replacement would have involved a complete reconstruction of the entire roof with a completely new roof. Due to the structure typology and its different parts, it would have been necessary to dismantle all the stone slabs, the underlying wooden planking, and the rafters. All these elements were still in a good conservation state but would have been damaged by the removal, and, therefore, difficult to be reused. That proposed solution was once again the proof that too often, a lack of understanding of building materials such as wood, sometimes leads to solutions that are completely inadequate, if not incorrect, when the skills that the restoration of timber structures requires do not accompany them: technological knowledge of materials and construction. Luckily, after the diagnosis and assessment of the state of conservation of the timber roof structure that was carried out, this initial solution was abandoned. The first diagnostic phase was followed by the second phase involving the definition of the restoration and reinforcement interventions and the execution of the works in 2000.

The intervention, agreed with the National Board of Antiquities, was aimed at the rehabilitation of the complex, with restoration and reinforcement interventions that would allow the original elements to be preserved as much as possible. Following the Principles for the Conservation of Wooden Built Heritage defined by ICOMOS [27], interventions followed the criteria of the minimal intervention capable of ensuring the preservation of the construction, saving as much as possible of its authenticity and integrity, and allowing it to continue to perform its function safely. Repairs of the original elements were carried out on-site, and the structure was strengthened as much as possible with traditional materials and techniques. In this specific case, reinforcements were based on the suggestions provided by the historic treatises that seemed more suitable and effective in guiding the rehabilitation intervention as respectfully as possible of the original artifacts, which, necessarily updated, have effectively led to the reinforcement interventions briefly described below. The techniques suggested by historic treatises have been applied not only for an overall improvement of the static conditions but also in the case of a specific lack of resistance and stiffness of the structure and localized decay of the elements. In particular, the decayed parts of the ridge beam were replaced with solid wood, properly shaped, and connected to the rest of the beam. The system was reinforced with the help of metal rods, thus achieving the strutting of the Polonceau truss [28, 29] (Figs. 9 and 10). Additional ventilation of the level under the roof was also provided with simple devices that allow natural air circulation without having water infiltration. Due to the limitation of the site (narrow streets of the village's historic center), the construction was also optimized by opening the roof from above and transporting the biggest element of the ridge beam (larch beam used for the substitution of the decayed portion) with a helicopter.

6.1. LOCALIZED REINFORCEMENT OF THE RIDGE BEAM WITH COMPOSITE WOOD-WOOD STRUCTURES AND STEEL ELEMENTS

For this intervention, the typology of "head" connections between the wooden elements was used, a technique of particular interest not only from a static point of view but also in the organization of the restoration site. This system was already in current use in the past to obtain beams of considerable length, as evidenced by the various treatises that report a great variety of solutions.

For this intervention, two head connections were realized to "recompose" the decayed structure to give continuity to the ridge beam. The interventions carried out have been:

- removal of the damaged section (length 4 m) and positioning of a sound wooden element (an old beam from a demolition of a wooden floor was used for this). For this phase, provisional support of the two parts of the ridge beam with tubular trellis resting on the perimeter walls was necessary so as not to overload the underlying stone vaults. The connections between the ridge beam and the new element were made on-site with "head" connections, also known as the double "dart of Jupiter" joints, tightened by three bolted stainless-steel collars. In this regard, it should be noted that the use of external stirrups (or through screws), required during installation, presents little guarantee of duration over time. A synthetic structural adhesive was therefore used to provide further unity in the parts where the two surfaces of the connections line up (Figs. 9 and 10);
- reconstruction of a sector of the beam, for the length of 2 m, with laminated wood realized on-site by adapting the boards to the cavity and fixed with a stainless-steel pin bonded with bicomponent resins.

6.2. REINFORCEMENT OF THE RIDGE BEAM WITH "REINFORCED BEAMS"

In addition to the interventions described above, the reinforcement of the ridge beam was completed with the realization of two reinforced beams, with double struts and double centering, with stainless steel rods – arranged in planes parallel to the lateral surfaces of the beam –, for the two spans of the continuous beam on three supports, respectively of 8 m of span. The intervention aims to stiffen the beam, which has an important deformation due to *fluage* (in the middle of the spans, the deflections are respectively 18 and 22 cm). The struts, placed at 1/3 of the span with a height of 0.80 m, are made of stainless steel with a thickness of 15 mm and are connected to the wooden beam with flanged and bolted collars. The ends of the tie rods are fixed to a steel collar whose anchoring is ensured by adjusting screws and stainless-steel pins. For all collars, deformable material (neoprene) has been interposed between wood and steel. In the middle of the beam, the tie rods are connected with a tensioner (threaded coupling) which ensures the initial tension setting, the control, or any eventual periodic adjustment (Figs. 9–11).

This type of work, with the use of two reinforced beams to increase the resistance and rigidity of the ridge beam, partially replaced with a wooden structure, proves that the teachings of Polonceau are still applicable today: a light and reversible intervention in which the combination of steel and wood guarantees the preservation in conditions of safety.

6.3. AN OVERVIEW 20 YEARS AFTER THE INTERVENTION

In Italy, at the time it was performed, the diagnosis and assessment of the timber roof structure of the church of Salbertrand (late 1990's) were particularly innovative to adopt such a multi-disciplinary methodology, involving also instrumental inspections that were relatively new. It was only starting from 2004, with the application in the diagnostic phase of the UNI Italian standards and with the definition of other international standards and guidelines for on-site assessment of historic timber structures

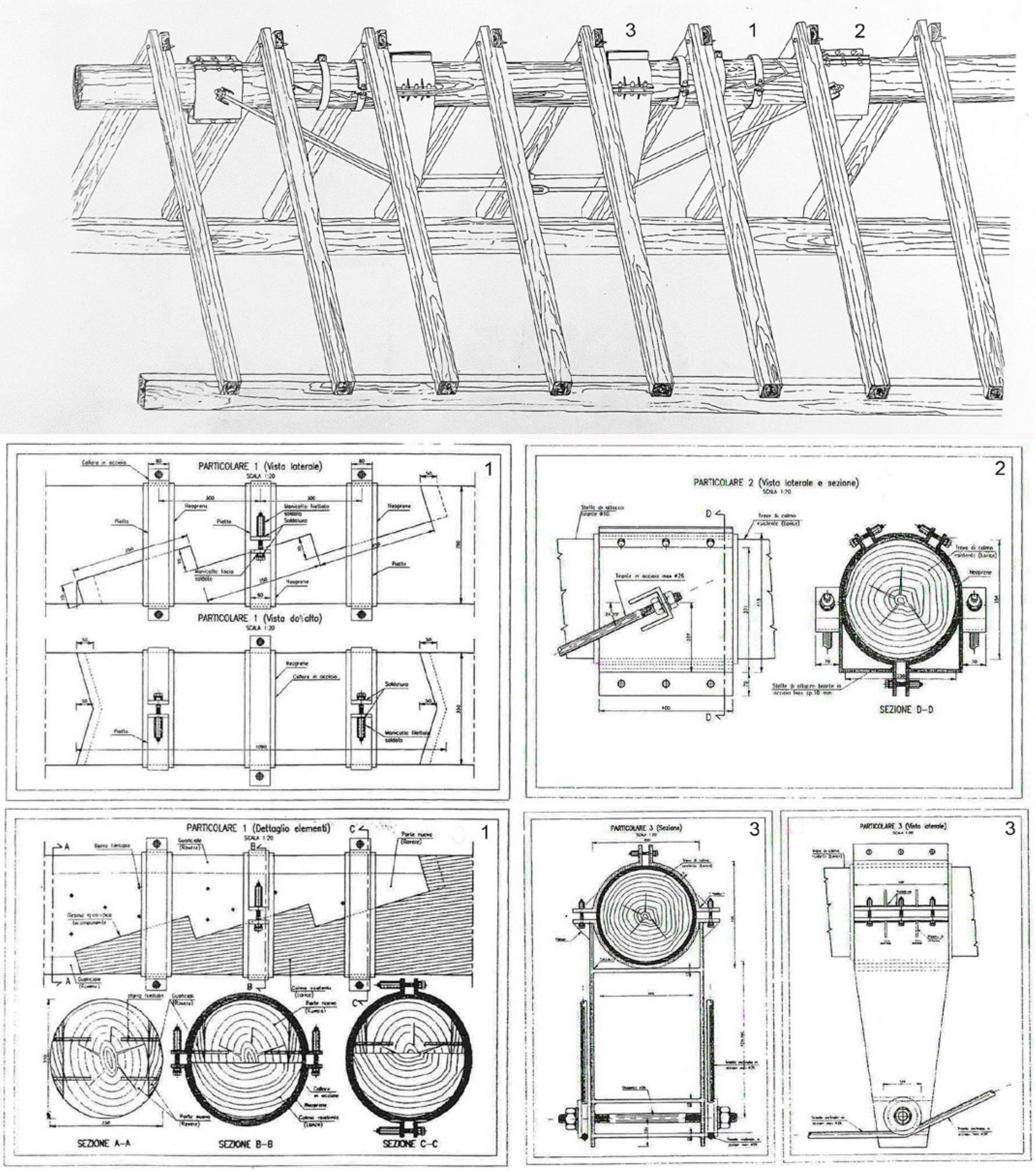

Fig. 9. *Church of Salbertrand. Reinforcement interventions on the ridge beam. General scheme of the interventions (on top); detail of the double "dart of Jupiter" joint, tightened by 3 bolted stainless-steel collars (1, on the right); and details of the stainless-steel tie rods and struts of the reinforced beam (2 and 3, on the left) system. (Image source: drawings courtesy of C. Bertolini-Cestari).*

Fig. 10. *Phases of the interventions carried out in 2000 with the integration of timber elements, the realization of the double "dart of Jupiter" joint, the transportation of the larch beam on the construction site, some details of the steel elements of the reinforced beam, and the scheme of the reinforcement intervention with Polonceau system. (Image source: drawings and photos courtesy of C. Bertolini-Cestari).*

[30, 31], that it was possible to obtain an evaluation of the mechanical resistances of the elements in a standardized manner. Over time, the diagnostic phase became increasingly accurate in defining the proposal of rehabilitation intervention. In the past few decades, technical and experimental research has developed survey methods involving various specialist areas, at times adapting knowledge from disciplines that do not belong to the construction sector (such as thermography, ultrasound, radiography, and tomography) and using the technological refinement of procedures inherited from research into architecture and technology of construction materials. In particular, non-destructive tests have become increasingly widespread, following new methodologies and diagnostic instruments, especially in recent years. Three-dimensional acquisition and modeling of structures, artifacts, and interior spaces can be based on LiDAR (Light detection and ranging) systems, photogram-

metry, and range cameras. Although, even if it was not yet so standardized and accurate, the diagnosis carried out in Salbertrand did already present the same primary objectives, and it was still possible to obtain important information that constituted an essential basis for the definition of the subsequent intervention phase.

The reinforcement interventions carried out in Salbertrand in the early 2000s as a reinterpretation of historical craftsmanship rules and traditions, which contemplated the use of steel devices, constitute an important reference given the assessment of the medium- and long-term durability of these interventions and the compatibility of different structural elements. Today, given the recurring requirements of conservation authorities in terms of the reversibility of interventions and compatibility between historical and new materials, an increase in the use of non-invasive reinforcement materials and reversible techniques was observed. Subsequently, engineers and researchers have increasingly employed stainless steel in retrofitting historic timber structures, also searching for innovative and advanced solutions [32–34]. Examples in which it is highlighted how steel (and in particular stainless steel due to its resistance to electrochemical corrosion facilitated by the absorption of the air humidity from timber members) is a suitable material to efficiently solve most of the static problems of timber structures, especially with the adoption of bar or cable systems placed in contact and forced to act in parallel with the existing structure, in order obtain several advantages: minimum intervention, the specificity of the solution with respect to the uniqueness of the object on which to operate, adaptability over time, low invasiveness, reversibility, recognizability, easy maintenance: a solution compatible and respectful of the existing structure and its original structural conception [35]. Steel allows interventions in line with the practice of conservative restoration, involving solutions placed side by side with the existing structures, without any subtraction, as a recognizable addition. The use of modern stainless steel and special tensioning makes solutions easy to adopt, light, removable, and cost-effective [36].

Visual inspections (according to the standard UNI 11119:2004 *Cultural heritage - Wooden artifacts - Load-bearing structures - On-site inspections for the diagnosis of timber members*) were recently carried out to assess the efficiency of the intervention and of the present condition of the joints (Fig. 11). The overall length of the ridge beam appears perfectly aligned. All the connections have also been checked and do not show any visible decay or alteration. Also, the connections realized with a steel tensioner (threaded coupling) are aligned and do not need additional settings or adjustment.

Wood moisture content was also recently determined through a portable resistance-type electrical hygrometer to assess the efficiency of the additional natural ventilation devices added during the restoration phase. An overall good condition was detected since all the wood moisture content measures were below 18%.

Regular visual inspections are planned, and in the future, it would be necessary also to carry out additional NDT investigations, numerical simulations, and monitoring to detect eventual movements in the structure and to assess the effectiveness of past interventions.

Fig. 11. *Church of Salbertrand. From left: Images of the roof structure in 2000 with the small portion of the roof that was opened during the intervention works, some details of the steel elements of the reinforced beam. Images of the roof cover with stone slates and the roof structure in 2021. (Image source: courtesy of N. Faure and R. Casse).*

7. CONCLUSIONS

Many structural renovations carried out in recent times have betrayed the idea of conservation, sometimes even involving the unnecessary demolition of centuries-old roofs. Such arbitrary or "excessive" interventions frequently stem from difficulties in assessing the state of conservation of the material and its actual load-bearing capacity, the incorrect evaluation of the structural behavior of these elements, or the adoption of superficial procedures guided by profit rather than by the real needs of the works in question. Despite the renewed interest in wood and the proliferation of studies on it, its load-bearing capacities continue to be questioned by operators. Their inadequate knowledge and lack of confidence in the material are revealed in their use of reinforcement techniques using supports made from innovative "new" materials deemed to solve all structural problems. Not only do such projects share a lack of confidence in traditional materials, construction techniques, and skills, but they frequently neglect one of the fundamental steps of structural renovation project management, the diagnostic phase. The historical knowledge of the construction is fundamental for any intervention.

This paper has presented some indications taken from the works of treatise writers. It illustrates how applying traditional rules of workmanship can attain the aims of preservation and structural efficiency with overall cost-effectiveness in recent restoration works. These intervention technologies could be defined as sustainable, with the use of simple steel elements, inspired by the construction rationality proposed in the middle of the 19th century by Polonceau: «[…] any construction system is required to meet the dual conditions of duration and economy, or, in other words, all materials used in a building system must be placed under conditions of resistance so that one can give them the smallest possible dimensions, and that their assembly should be of the greatest simplicity […]» [13].

Introducing these criteria in new projects can increase the quality of the interventions compared with those achieved using other technologies that still leave some doubts about their durability and reliability. In the final balance, the successful outcome of the intervention on the timber roof structures of the church of Salbertrand is the result of mindful design proposals that reflect the close link between the diagnostic phase before the final project and the investigations that preceded the executive project. The possibility of assessing the overall good state of conservation of these reinforcement interventions nowadays, some twenty years after their undertaking, could constitute an essential reference for future interventions. The durability and reliability of this and other reinforcement techniques presenting innovative features need to be evaluated through surveys conducted on the broadest possible statistical sample [37, 38]. These surveys allow us to better address and plan reinforcement and to study the actions required to prevent the medium- to long-term adverse effects of these interventions.

In conclusion, this research project confirms the usefulness of learning from tradition in the multi-disciplinary activity that involves a vast number of various professional figures, such as architects, civil engineers, wood technologists, and dendrochronologists, with the supervision of national boards responsible for the safeguarding of structural interventions on buildings belonging to our historical-environmental-cultural heritage.

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