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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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REINFORCEMENT METHODOLOGIES OF TIMBER ELEMENTS IN HISTORIC TIMBER ROOFS

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Abstract

This paper aims to present a comprehensive review of the reinforcement of historic timber roofs, focusing on their main characteristics, advantages, and disadvantages, which would help professionals select and define the design of reinforcement solutions. Cultural heritage issues are taken into consideration. Reinforcement can be done via different methods – traditional and modern – using simple or sophisticated techniques. An overview of the main materials and the techniques used for selected case studies are presented, illustrating how various reinforcement methods are implemented in practice.

Keywords

Historic timber roofs, Architectural Heritage, Reinforcement, Techniques.

1. INTRODUCTION

Historic timber roofs constitute an important part of the cultural heritage of many countries of the world. The increased sensitivity towards the preservation of cultural heritage has led to the adoption of restoration techniques that comply with generally accepted conservation principles and guarantee, as much as possible, the preservation of authenticity and integrity of the structure, minimal interventions, reversibility, and compatibility with the original parts of the timber [1, 2]. Economic, environmental, historical, and social reasons dictate the aim and scope of intervening in historic structures.

Repair and/or reinforcement is preferred to total structural replacement since the authentic materials and structural systems, the construction technology, and workmanship constitute a significant cultural value of historic buildings. They need to be protected and preserved, even if they may no longer be visible, hidden by plasters or ceilings, after the restoration [1, 3]. This growing sensibility towards the preservation and maintenance of heritage buildings, the various species of wood and the complexity of their structural behavior, their degradation caused by different agents, and the need for rehabilitation to incorporate new uses has led researchers to study various repair and reinforcement solutions.

In most cases worldwide, traditional buildings involve timber used at least as floors and roof systems. The technical and technological development of roof carpentry was very different from country to country. Many different types of roof structural systems and joints exist, which bears testimony to the diversity and richness of the timber cultural heritage and, at the same time, to the difficulty of studying, repairing, and reinforcing them.

Reinforcement or strengthening deals with interventions that increase and upgrade the original or existing load-bearing capacity of the structures, while maintenance and repair try to recover the original load-bearing capacity and return the existing fabric to a known earlier state. Reinforcement is usually applied to extend the use of structures approaching the end of their design life and to ensure that recent requirements for a new use of a building ("heavier" loads or level of safety) and changes in regulations are fulfilled.

Each reinforcement solution has advantages and disadvantages regarding conservation philosophy, architecture, aesthetics, structural performance, and technological and construction quality. Economic issues such as the cost of the intervention and the availability of specialized staff can also determine the choice of the method used [4]. When the reinforcement of a roof is being designed, all of the above has to be taken into account and evaluated carefully to ensure that the proper intervention is chosen. A careful choice of strengthening materials and the reinforcing method is necessary. No material or method can be considered the optimal one. Each case is unique.

This paper will focus on reinforcing historic timber roofs but not reinforcing existing ones, which constitutes a much wider group [5]. It also focuses only on reinforcement methods for the main load-bearing timber elements, not considering the secondary ones (purlins, decking), non-structural parts such as roofing or ceiling materials (clay tiles, timber shingles, ceiling planks, etc.), and reinforcements of connections, which constitute a vast area of research and case studies. Some examples that improve the overall behavior of the roof are included since the decision to use them may indirectly be beneficial for the load-bearing capacity of the timber members of the roof, diminishing, for example, the loads that will carry.

In several cases, roofs have important decorative (woodcarving and polychrome) details, markings, symbols, and finishes, and very often, they carry simple ceilings or ceilings with very high artistic value. In many of these cases, it is required to operate on the spot, without dismantling the carpentry or any of its parts, increasing the difficulty of both the assessment and the restoration procedure.

2. CAUSES OF DAMAGE TO TIMBER ROOFS

The first step before any intervention (repair or reinforcement) is the documentation and the assessment of the existing timber structure: the understanding of the structural system, the damage and the causes, and the residual strength and stiffness properties. Briefly, the most common and major problems of timber roofs are: i) decay problems, usually in parts in which water enters and accumulates, such as in support areas (timber parts embedded in the external walls); ii) insect attack (active or not); iii) damage or lack of strength and/or stiffness of single members (failures, shrinkage cracks, excessive deformations, etc.); iv) damage or lack of strength and/or stiffness of joints (failures, shrinkage cracks, etc.); v) lack of stiffness of the whole timber roof (in-plane or out-of-plane, vertical or horizontal deformations).

Damage and failures of timber roofs can be due to different causes: i) natural defects of wood; ii) biological degradation (rot, insect attack); iii) environmental and atmospheric agents (changes in wood moisture content); iv) fire; v) errors in the original conception/poor original design (lack of adequate sections, poor quality of timber, errors in the original structural system); vi) poor execution; vii) excessive loading (wind, earthquake, etc.); and, viii) maintenance or intervention errors during their lifetime.

Proper assessment with appropriate techniques is obviously of major importance. Therefore, the study of relevant state-of-the-art reports, scientific work, and publications concerned with diagnostic procedures is highly recommended [5–7].

3. REINFORCEMENT METHODS

In the next sections, different examples of reinforcement methods will be presented according to the following categories: i) reinforcement of timber roof members (rafters, tie-beams, posts, end-beams, etc.); ii) reinforcement of the overall load-bearing system of the roof (improvement of the overall stability, e.g., bracing).

3.1. REINFORCEMENT OF TIMBER ROOF MEMBERS

In order to increase the flexural strength and stiffness of timber members (beams), reinforcing elements are usually added to supplement the existing elements. A large variety of reinforcement configurations are available. The reinforcing elements can be in the form of rods, plates, straps, or other structural shapes, which are connected to the beam using mechanical fasteners or structural adhesives. These reinforcing elements can be placed inside or outside the member and may be passive or pre-stressed. Apart from the structural requirements, the strengthening configuration selected for a particular application may depend on other factors, too: aesthetics can limit the use of different materials; the presence of decorative ceilings or painting on beams may require that the reinforcement be restricted to the top or the sides of the timber elements; fire protection, aesthetical issues, and other requirements may exclude the use of externally bonded plates on exposed surfaces; geometrical, architectural or constructional limitations can restrict the use of new elements or elements with certain dimensions; etc. [8].

3.1.1. PRE-STRESSING METAL REINFORCEMENT

Pre-stressing has emerged as one of the most common reinforcement techniques for increasing the bending load-carrying capacity and the stiffness of timber members when large deflections are observed. It is mainly used for rafters and tie-beams and may be required due to an inadequate section or low strength and stiffness properties. An essential advantage of this reinforcement type is its reversibility.

In publications since the second half of the 19th century, it is emphasized how the empirical work of many engineers has created a broad selection of layouts and structural solutions that have worked properly for many decades (Figs. 1 and 2). Technical manuals refer to this kind of reinforcement, mainly pointing out the difficulties of installing the outer tendons at the head of the beams due to the fact that the beams are embedded into the walls [9–11]. Of course, there have been improvements in these techniques since then, boosting confidence in the use of this kind of reinforcement.

It was in the 2nd half of the 20th century that a systematic approach to post-tensioning restoration methods of timber structures was established. Some examples were reported in manuals written during that period and are still a reference for present professionals. Most of the leading restorers belong to the Italian school, which is known as a very active center for restoration theories and projects (Fig. 2) [12].

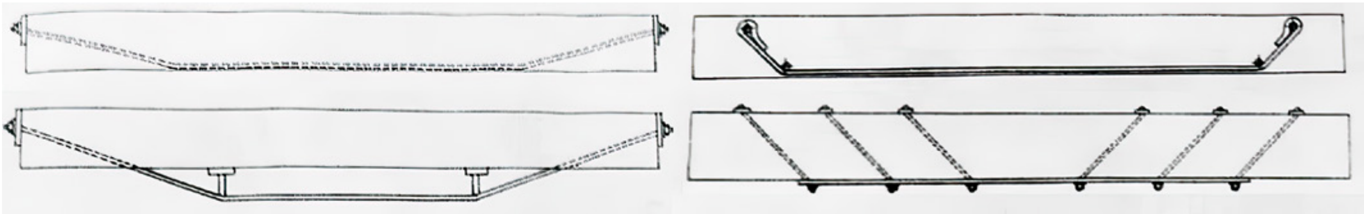

Fig. 1. *Different pre-stressing techniques for strengthening existing timber beams [9–12].*

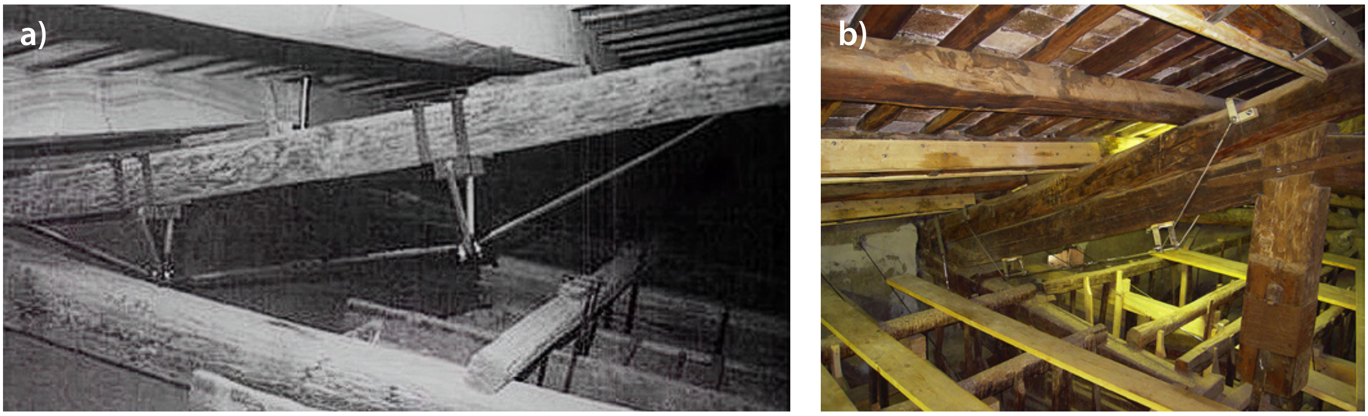

Fig. 2. *Reinforcement of a truss rafter in the theater of Sarteano (a) and a Renaissance palace in Rome by G. Tampone (b) [12].*

Nowadays, for the reinforcing system, high-strength materials with minimum dimensions, such as steel (stainless or not) or titanium, can be used. This reinforcement system can be applied to sound, unbroken beams of very regular shape or to members that have already been repaired [9]. One major issue that needs special attention is how the rheological behavior of the material and the shrinkage of the timber sections may affect the loss of pre-stressing, especially in cases where the application of the load is transferred by perpendicular compression or at an angle to the grain. Tension perpendicular to the grain should be avoided. Periodic inspections are necessary for the pre-stressing methods to ensure the intervention's efficiency according to the design specifications.

3.1.2. NON-PRE-STRESSED METAL REINFORCEMENT

A similar concept to the above, but without pre-stressing, can be used to reinforce tie-beams that present excessive deformation. Steel elements may support the transfer of loads by the tie-beam to other elements (members or joints), which are carefully chosen and verified structurally (Fig. 3) to ensure the safe transfer of the forces through the new load path.

The effect of the environment and the material's initial and existing conditions, even the conditions after the restoration works, must be taken into account, too [9].

3.1.3. CONNECTION OF NEW ELEMENTS (TIMBER-BASED OR STEEL) TO THE EXISTING TIMBER MEMBERS BY STEEL FASTENERS

This is a common technique of reinforcement used to increase the load-carrying capacity of a timber element (e.g., a rafter or a tie-beam) or if the deflection of the beams is too high. Steel sections and plates [10], solid timber sections, or wood-based products (glued-laminated timber, plywood, cross-laminated timber, laminated veneer lumber, etc.), nailed, screwed, or bolted either to the tensile face or the vertical sides of the timber beams, are used to repair or reinforce timber elements (Figs. 4–6). Similar techniques are used for the substitution of the decayed parts of timber members. For a systematic review of the repair and reinforcement of historic timber structures with stainless steel, see Corradi et al. (2019) [10].

As timber beams generally fail in tension in a brittle way, positioning the reinforcement at the tensile face of the beams is very effective for increasing bending strength. The above interventions, in most cases, are not applicable to exposed timber structures. Besides its poor aesthetic appeal, reinforcement with external metal plates may suffer other disadvantages due to condensation on the timber members and their consequent vulnerability to decay. Dimensional changes in the steel parts are caused by changes in temperature and, therefore, additional internal stresses in the wood and fasteners and dimensional changes of the timber that the steel parts

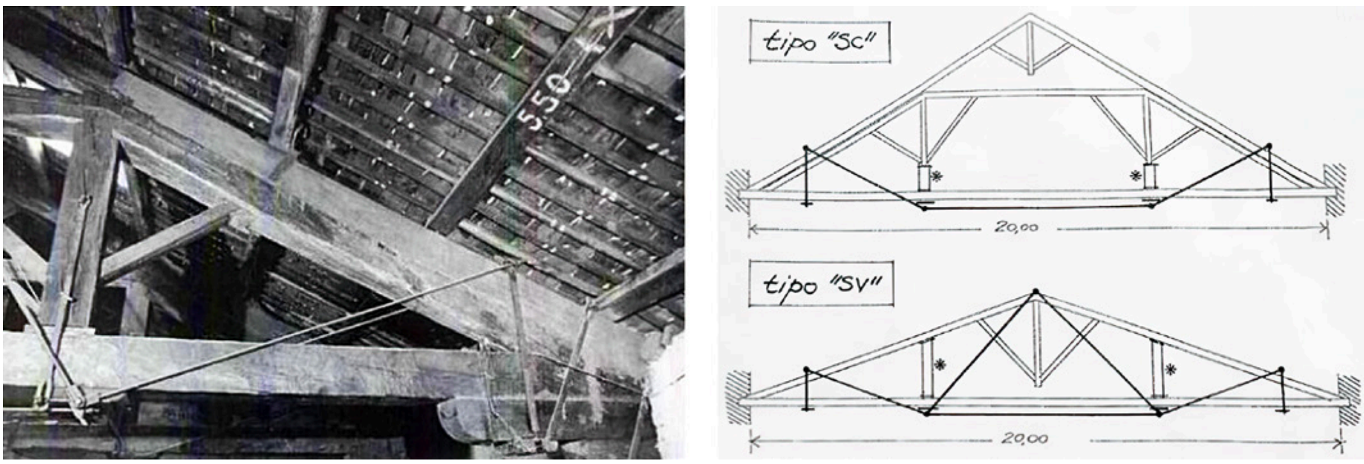

Fig. 3. *Reinforcement of a truss tie-beam. Detail and design schemes of the Savona Theatre project. (Image source: courtesy of the designer, ing. L. Paolini).*

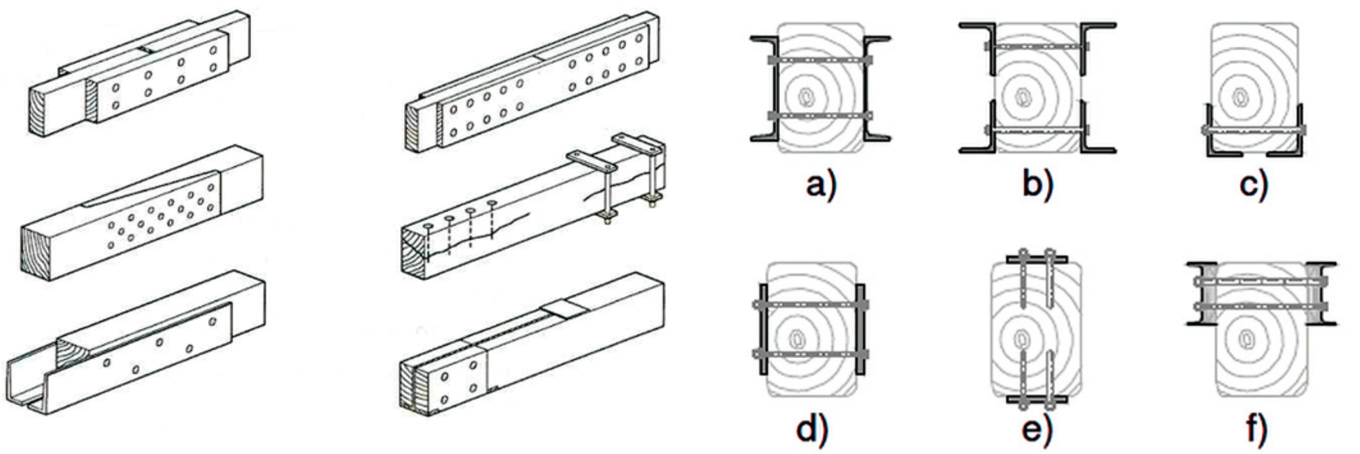

Fig. 4. *Repair or reinforcement of timber members using new timber elements or steel plates and sections connected to the original timbers by metal fasteners [13, 4].*

Fig. 5. *Repair of a timber rafter using large pieces of wood screwed at the sides of the rafter [14].*

cannot adapt to if humidity changes occur. Galvanized steel or protected from corrosion sections, plates, or fasteners would be preferable. On the other hand, when adding steel elements, due to the different modulus of elasticity, it is crucial to take into account that stiffness incompatibility can arise.

Internal elements such as steel plates inserted in the timber members can be used too. They can be connected to timber beams with screws, steel dowels, or bolts (Fig. 6).

The system can be applied to undersized, overloaded, or broken timber members. It requires geometric regularity of the section of the timber member. For a well-sized but broken element, the length of the inserted plate can be limited to the length of the affected section plus an additional length (one and a half the depth of the member), including sound wood at both sides [12]. Strengthening of timbers with steel flitch plates and resin working as a composite member is a method used in several restoration projects in England (Fig. 6d). However, again, it is important to assume that incompatibility issues can arise due to the different stiffness and dimensional stability presented when distinct materials – steel, resin, etc. – are used together in a composite section.

Fig. 6. *Strengthening of a timber member by insertion of steel plates. Invention patent G. Tampone, L. Campa, 1987 (a) [12]. Barn (14th century) in Herefordshire, UK (Sinclair Johnston, 2009). Truss repair using a 20-mm thick steel flitch plate and resin. If resins were not used, many bolts would have been required, further cutting away the fabric and having less aesthetic appeal (b-d) [15].*

3.1.4. ADDITION OF NEW TIMBERS (STRUTS OR POSTS) TO INCREASE THE SUPPORT OF THE EXISTING TIMBER MEMBERS

This is a typical reinforcement method for "post and beam" roofs, the most common type of roofing for buildings in the Balkan and Minor Asia areas during the Byzantine and Ottoman periods [16]. It is a spatial system that functions in a completely different way from the well-known types of king or queen post trusses widely used in Italy and other European countries. The loads are transferred from the rafters through a three-dimensional system of beams, posts, and struts not only to the outer walls but mainly to the internal ones (Fig. 7).

In the "post and beam" system, the connections of the posts and struts can transfer compression forces but not tension. Typical damage of such roofs is the bending failure or excessive deflection of the longitudinal horizontal beams that support the rafters (Fig. 13a) due to the absence of adequate struts or lack of appropriate sections. The reinforcement of the original load-bearing system can be accomplished by the addition of new struts (denser supporting) (Fig. 7c), which is an easy, low-cost and reversible intervention that gives the possibility to keep the original beam in position and retain the concept of the original structural system [15, 17].

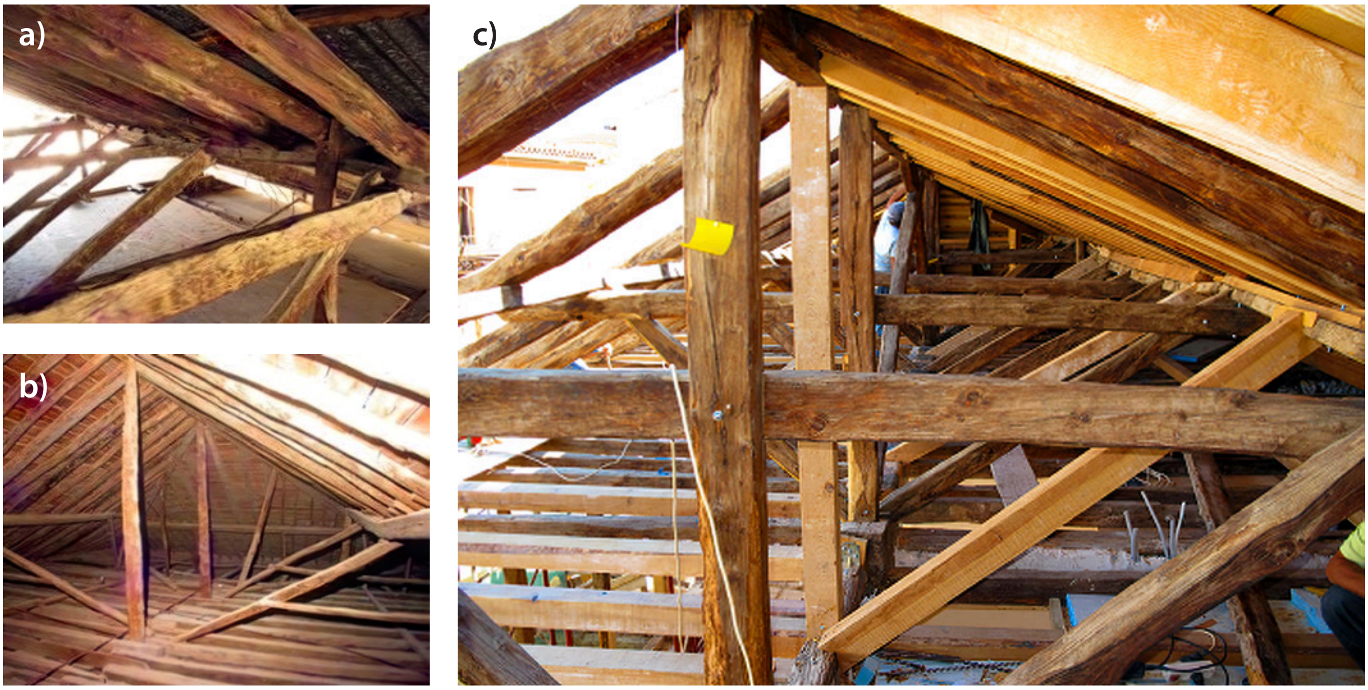

Fig. 7. *"Post and beam" roofs of the Ottoman period mansions in Greece. Excessive deformation of the longitudinal horizontal beams that support the rafters (a, b) [17]. Reinforcement by adding new timber posts and struts to increase the supports of the longitudinal beams that carry the rafters (c) [18].*

3.1.5. ADDITION OF NEW TIMBER OR STEEL MEMBERS NEXT TO THE ORIGINAL TIMBER MEMBERS OF THE ROOF

In some cases, new timber or steel elements can be placed parallel to the original ones without any connection to diminish the loads the existing elements carry (Fig. 8). The concept of this reinforcement is similar to the one described in section 3.2 regarding the whole roof structure.

3.1.6. REPLACEMENT OF THE WHOLE TIMBER MEMBER

There are cases (poor initial construction, severe damage or failure, etc.) where the replacement of the whole timber member (rafter, tie-beam, post, strut, etc.) is the only solution. But this should be resorted to only as a last alternative in any restoration project (Fig. 9).

3.1.7. BEAM-END REINFORCEMENT (PROSTHESIS)

Intervention in roofs very often involves end-beam repairs. End-beams embedded in masonry walls are the most exposed zones to biological agents. If a high level of moisture is present in the masonry, for example, due to infiltration when damage occurs in the roofing elements (e.g., tiles), and the adsorbed moisture cannot evaporate because of poor ventilation, the suitable conditions for biotic attacks (moisture contents above

Fig. 8. *New timber or steel elements placed between the original beams to carry part of the loads (a) [19]. Queen's Tower Estate Ilion, Athens: New steel tie-rod added next to the original timber tie-beam without any connection to transfer the tensile loads (b).*

Fig. 9. *New timber beams used to replace only the severely damaged rafters (a, b) [18]. The Neoclassical School in the Medieval city of Rhodes: New timber glued laminated beam replaced the poorly constructed original horizontal beam (c).*

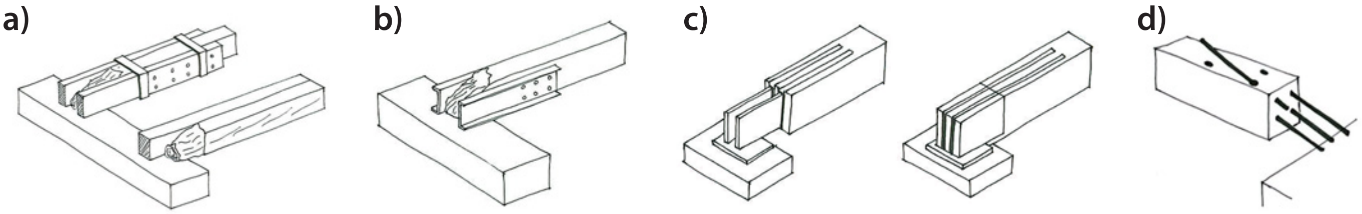

Fig. 10. *Examples of end-beam repair techniques (prosthesis) using different materials and methods [9]: (a) new timber elements connected to the sound part of the original timber with steel straps, plates, and steel fasteners; (b) new steel elements used to replace the decayed timber; (c) glued-in plates connecting the prosthesis to the sound part of the original timber; (d) glued-in rods connecting the prosthesis made either of wood or resin.*

20%) are established, and degradation of end-beams can, therefore, be expected. Nowadays, several techniques and methods can be found in the literature to repair and reinforce rotten timber end-beams. Since the early 1970s, many companies have developed materials and techniques to repair timber elements by partial substitution of the decayed part (design of a prosthesis). All of these techniques aim to restore the load-bearing capacity of the original member and the old part's structural continuity with the new, thereby ensuring their connection and collaboration.

The intervention consists of the substitution of the decayed part by a new element which can be made of solid wood or wood-based products (glued-laminated timber or LVL) (Fig. 10a-d), steel sections or plates (Fig. 10b), or epoxy resin (Fig. 10d). Such new elements are connected to the original timber part by steel fasteners (nails, screws, bolts, dowels, metal straps, etc.), by threaded or ribbed steel glued-in rods (GiR), or by FRP plates, woven fabrics and rods (from glass, carbon, aramid, basalt, etc.). The elements used to substitute the decayed timber may be visible or not, and the elements that connect them to the sound part of the timber can be either external or internal [9].

The use of prostheses became widely accepted mainly due to their low intrusion level, simplicity of design and execution, and the good aesthetic result of some of the techniques used. The type of prosthesis reinforcement method may vary, depending on many parameters (cultural values, aesthetics, presence of decorative elements, access to the damaged timber part, fire protection, on-site application, available expertise, cost, etc.).

The above methods of prostheses, especially the ones that use timber, offer several advantages: high connection stiffness without significant settling; the possibility of ductile design with yielding of the steel or the other types of bars in spite of the adherence based on glue; protection of the glue and the embedded elements from chemicals and fire; unmodified exterior of the reinforced element that maintains the original architectural characteristics [20]. A major advantage of the glued-in rod connections is the transfer of forces directly into the inner part of the members' cross-section [17]. On the other hand, several considerations have been raised for some of the methods used. The use of timber prostheses compared to resin or steel is considered to follow more closely the conservation principles of historic timber structures [1]. For the use of external steel elements (sections or plates) and the problems that may arise, see section 3.1.3 (Fig. 11). The reinforcement design for members or joints should consider the effect the reinforcement can have on the original structural system, which needs to be preserved, except for cases that present important errors in the original conception (Fig. 11). Changes in beam or joint stiffness (resin prosthesis or some cases of steel plates) may have consequences on the overall behavior and load distribution of the entire structure, altering the paths of loads and leading to damage or failures of the weaker elements.

In cases where steel is used, problems may arise due to environmental thermal or humidity changes in steel and timber. As the reinforcing elements generally have different stiffness, thermal expansion, and moisture absorption properties than the timber elements, factors that constrain shrinkage and swelling due to thermal or moisture changes must also be considered. If necessary, additional thermal or moisture-induced stresses should be accounted for in the design (Fig. 12) [8].

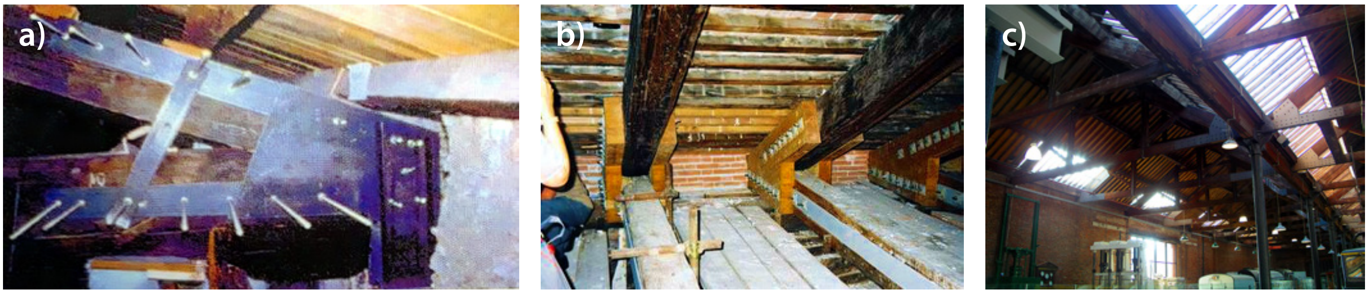

Fig. 11. *Interventions that may change the stiffness properties of the original semi-rigid joints [20].*

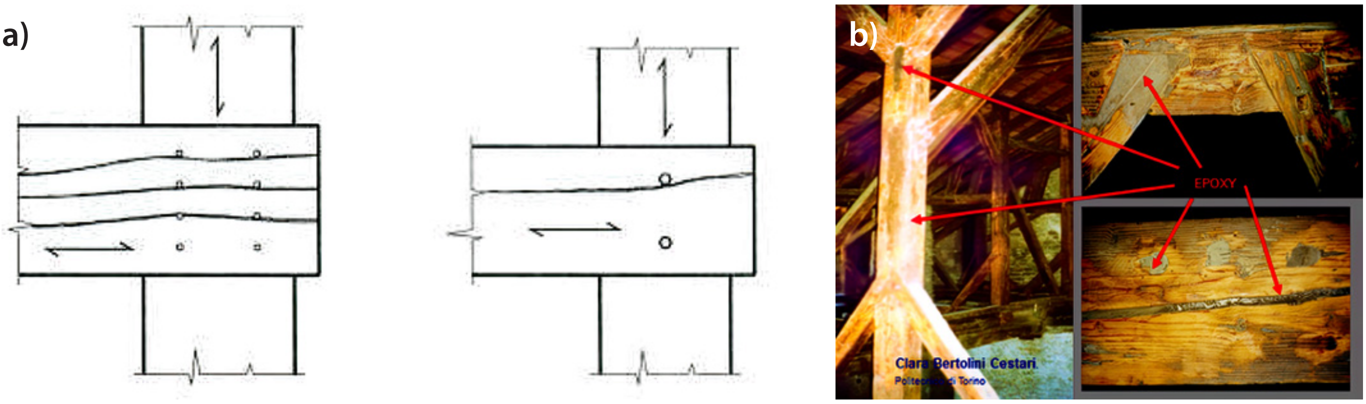

Fig. 12. *Cracks caused by differential shrinkage parallel and perpendicular to the grain in the timber-to-timber connection (a) [21]. Improper filling of the shrinkage cracks with resin (b) [22].*

Some interventions have caused further damage to structures in the past due to a lack of knowledge on selecting and implementing appropriate reinforcement methods. An example is the filling of shrinkage cracks with resins. The excessive stiffness of the adhesives and their subsequent inability to withstand the timber strains, especially strains due to hygrometric variations, can seriously impact the state of the existing cracking and even provoke new cracks (Fig. 12). The same applies to the use of bars glued to timber to stop the further widening of cracks. The use of such a technique can create undesired stress states by preventing the natural movement of the timber. Moreover, questions related to the compatibility of reinforcing and reinforced materials, the significant differences between the properties of wood, a hygroscopic organic material, and those of epoxy, an impermeable plastic, the durability, the low reversibility, the sufficient reliability needed for historic structures, the behavior of the resin under thermal and moisture fluctuations, as well as the long-term performance and fire resistance of the resin are yet to be investigated. Timber experts do not recommend epoxies for external repairs due mainly to moisture issues [23, 24].

3.2. REINFORCEMENT FOR THE OVERALL LOAD-BEARING SYSTEM OF THE ROOF

3.2.1. ADDITION OF A NEW STRUCTURAL SYSTEM IN PARALLEL TO THE ORIGINAL ONE

Rafters or tie beams (see 3.1.5), or even a whole roof truss, can be introduced between the main beams or the main trusses (placed parallel to them). An example of an added parallel system can be found on the roof of the Salone dei Cinquecento in Palazzo Vecchio in Florence (Fig. 13a) and in the main railway station in Wroclaw, Poland (Fig. 13b).

Roofing structures, in several cases, carry ceilings of great artistic value. The reinforcement may concern the increase of the load-bearing capacity and, mainly, limiting the deflection of the roofs since, in many cases, the ceilings support frescos which are brittle without any ductility. This is the case of the king post timber roof designed in 1563 by Giorgio Vasari for the Salone dei Cinquecento in Palazzo Vecchio in Florence (a project carried out 1563-1565, by Battista Botticelli), which had to carry a very

Fig. 13. *Salone dei Cinquecento in Palazzo Vecchio, Florence. General view of the two trusses for the roof at the back of the photo (the original one) and the new one at the front (a) [25]. Main Railway Station in Wroclaw: A new load-bearing structure for the ceiling (a steel space frame) was used to relieve the roof truss from the coffer ceiling loads (b) [26].*

heavy ceiling of great artistic value. The ceiling was soon affected by sagging caused by creep effects. A reinforcement work was carried out in 1854 by Arch. D. Giraldi, who constructed new timber trusses, placed at a lower level as a parallel system between the original ones without any intervention at the old ones (Fig. 13a) [25].

3.2.2. ADDITION OF NEW STRUCTURAL SYSTEMS TO IMPROVE THE OVERALL PERFORMANCE AND STABILITY OF THE ROOF

Besides the behavior of the individual structural elements (members and joints), which has an indirect but considerable impact on the overall behavior of the system, reinforcement may be needed to improve the original structural system that presents either design or execution errors, to confront a severe deformation of the whole roof or an overall stability problem that needs bracing (Fig. 14). The advantage of these solutions is that they are reversible.

Another example of this type of reinforcement was used in Angera Castle (Lago Maggiore, Italy), where all loads are transferred after the intervention to the supports by a new steel truss, although originally, the loads were divided across four supports [28].

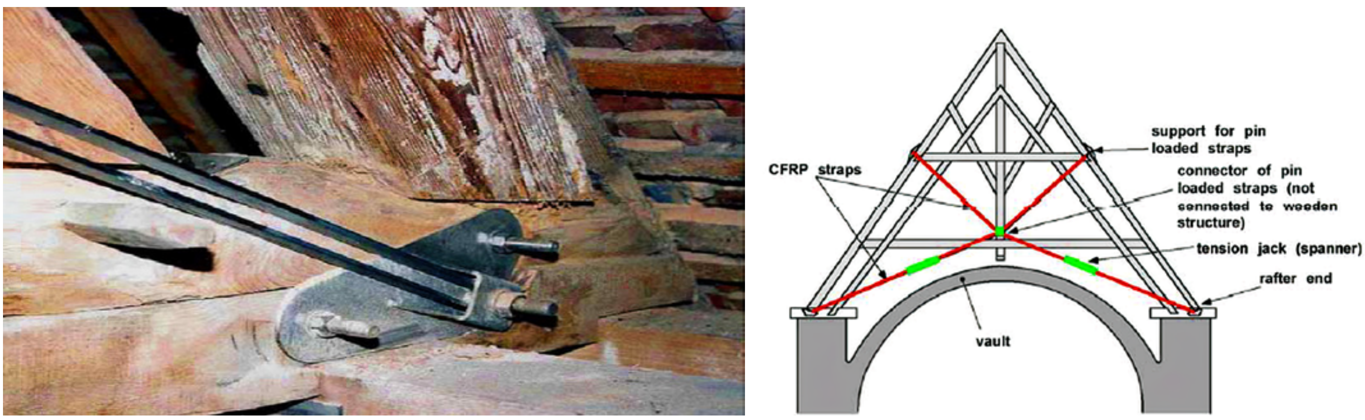

Fig. 14. *St. Marien Church. Reinforcement of the timber roof using unbounded pin-loaded CFRP straps [27].*

4. CONCLUSIONS

When new usage and/or new imposed loads are introduced, reinforcement of traditional timber structures is needed. If the decay of timber elements is huge, then local replacement of the decayed part is the best solution. When interventions are necessary, specific and reliable on-site assessment techniques are required to determine the appropriate level of intervention needed. A critical point remains the evaluation of the replacement, repair, or reinforcing solutions, along with the cultural significance, the know-how, and the associated project costs of each case. Assessment of the durability of the intervention work carried out with new innovative techniques is necessary too. The use of wood to solve problems of wood offers one of the most interesting features in conservation, compatibility.

For timber members, reinforcement helps to restore the load-bearing capacity lost because of the material decay and increases the resistance (strength and stiffness properties). Current knowledge of reinforcement methods of existing structures is largely based on practical experience. Unfortunately, the study of reinforcement techniques still needs to be included in European standards such as the Eurocode 5 (EN 1995-1-1) [29], but only for specific aspects in the National Annexes of some countries.

Investigations on that promising topic have helped experts figure out how to overcome timber weaknesses, resulting in design models and reinforcement methods proposals. Some of the most important and applicable outcomes will be integrated into the revised edition of the Eurocode 5 to help engineers design reinforcements for timber structures. It must be pointed out, though, that these reinforcements are for new timber structures. Since existing structures and, mainly, historic structures still need to be covered by the latest standards, it is urgent to develop relevant European Standards too. Thankfully, in 2017, to close a part of the gap between practical needs and missing standardization, the European Standardization Committee responsible for the Eurocode 8, CEN/TC 250/SC 8 concerning earthquake design, decided to add in chapter 3 for existing buildings a section on existing timber structures, historical or not.

Increased knowledge and research on retrofitting techniques are of great importance to support the Standards that are being or will be developed. When timber structures are reliably repaired or reinforced, structural failures and unnecessary replacements can be avoided, and sustainability, which is essential from economic, environmental, historical, and social perspectives, will be served too. Standards, research, and the constant and continuous dissemination of knowledge, mainly through education, can provide the necessary tools for structural engineers, who are often part of a multi-disciplinary team and have to work together in a restoration project to evaluate the existing condition of a historic timber structure. Moreover, these tools may help in the selection of the proper interventions using innovative and/or simple techniques that will sustain the authenticity of our architectural heritage, including the authenticity of the "invisible", in many cases, timber load-bearing structures.

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Authors contribution

Filipa S. Serino, writing, investigation and editing; Eleftheria Tsakanika, conceptualization, methodology, writing and review, supervision; Jorge M. Branco, conceptualization, methodology, writing and review, supervision; Paulo B. Lourenço, conceptualization, supervision.

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