The timber roof structure of Chapel XVI at Sacro Monte of Orta: an example of conservative strengthening work

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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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THE TIMBER ROOF STRUCTURE OF CHAPEL XVI AT SACRO MONTE OF ORTA: AN EXAMPLE OF CONSERVATIVE STRENGTHENING WORK

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Abstract

The principles of conservation of existing structures (like evidence of regional construction techniques) pose a significant challenge in the general field of structural safety, increasingly claimed by the new technical codes. The restoration building site of Chapel XVI at Sacro Monte of Orta San Giulio (Italy) testifies to a respectful design approach to enhance the timber elements still recoverable without distorting the original static scheme. The preliminary knowledge phase allowed for correctly interpreting the historical construction phases (including analysis of archival documents and diagnostic investigations), the vulnerabilities of the roof structure, and the peculiarity of the stone roof covering as a construction technique to be preserved and improved. The recovery project has exploited the potential of the laser scanner and micro-invasive diagnostic techniques to move towards limited replacement choices of wood elements that could no longer be recovered. The recovery of the roof of the XVI Chapel, as a pilot building site of an international research project on the maintenance of historical sites (INTERREG ITA-CH "Main10ance"), is evidence of a fruitful multidisciplinary discussion aimed at improving the methodological approach to the strengthening work of historical structures.

Keywords

Maintenance, Historical buildings, Timber roof structures, Strengthening work, Structural safety.

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1. INTRODUCTION

The restoration building sites are increasingly interested (also) by structural safety interventions to reduce static and seismic risk. The recent Italian technical codes [1–3] already provide a gradual approach to the existing built heritage through diversified phases of structural improvement by strengthening works that do not compromise the original structural construction concepts. Following the countless collapses and immeasurable losses of historical buildings severely damaged by the latest Italian seismic events [4–8], structural security becomes more and more a need to be pursued: conservation cannot be guaranteed without safety. However, reaching structural safety levels comparable to those required for new constructions becomes a challenge within a restoration site, where safety and conservation must dialogue together without prevailing one over the other in an aprioristic way. If anything, when timber structures have a high value of technological evidence, conservation has a prevailing hierarchical position in interventions.

This paper describes the methodological approach, the design process, and the execution of the maintenance works for the timber structures and roof covering in the XVI Chapel at the Sacro Monte of Orta. The intervention was scientifically monitored within an international research project (European Research Prog. INTERREG Italy – Switzerland "Main10ance"), which has as its theme the good practices of scheduled maintenance of big architectural sites [9].

The Sacri Monti of northern Italy is a UNESCO heritage site that includes nine complexes consisting of groups of chapels and other buildings with many artistic masterpieces. All buildings are part of a high-quality natural environment. The first complex was founded in the late 15th century in Varallo Sesia, and the others were constructed up to the end of the 17th century and dedicated to different aspects of the Christian faith [10]. The landscape context in which these sites are built is very suggestive and in close contact with the environment. However, it also involves greater sources of degradation on the plasters [11], walls, and roof systems due to many causes, including (principally) humidity. It is, therefore, essential to plan maintenance with good intervention practices, evaluating not only the compatibility of the restoration materials but also developing non-invasive diagnostics methods to monitor the decay of the materials [12].

The Sacro Monte of Orta is located on a wooded peninsula that juts into Orta Lake. The first idea for a new religious complex in Orta dates back to 1583, modeled after the religious itinerary of the Sacro Monte in Varallo. It only became a reality in 1590, thanks to the contribution of Abbot Amico Canobio from Novara and according to the project of Capuchin architect Cleto from Castelletto Ticino. Twenty chapels immersed in a natural surrounding illustrate episodes from the life of St. Francis, with sculptures and paintings, distributed along a path that winds on the top of the hill, opening up spectacular views of the lake and the island of San Giulio. Statues and paintings create scenes of deep realism: the intimate and natural atmospheres typical of early seventeenth-century Lombard art are combined with the lively theatrical Baroque style of the end of the century [10]. The route ends at the Church of St. Nicolao; a proto-Romanesque building completely redesigned during the seventeenth century to recreate the spaces of the lower Basilica of Assisi. In the last decade, some studies have underlined the relevance of the relationship between the architecture, the masterpieces of Sacro Monte, and the landscape (with his anthropic transformations due to centuries of men's work on the natural environment) along with the importance of a planning policy imprinted towards the respect and the safeguard of the stratification of significant elements [13]. Among these chapels is the XVI, dedicated to *St. Francis, who returns to Assisi from the Verna before dying* (Fig. 1). Like all the historical buildings belonging to the monumental complex of Sacro Monte of Orta, the XVI Chapel was characterized by a stone masonry structure, an attic vault, and a stone roof with timber structures.

The timber roofing structure was in a decaying condition and therefore required maintenance interventions, including the partial replacement of the stone slabs and the safety improvement of the timber framework. A survey phase with laser scanners and resistographic tests on the timber elements anticipated the design project. This survey phase revealed a significant number of degraded elements; however, the repair project was oriented towards preserving many parts, limiting replacements, and eventually carrying them out with the same wood species and similar dimensions to the original elements. At the same time, it was necessary to solve some vulnerabilities of the nodes of the roof structures in order to strengthen their static resistance and reduce the seismic risk.

Fig. 1. *The XVI Chapel at the Sacro Monte di Orta.*

For this purpose, the design approach and guided execution of the restoration work in the XVI Chapel represent a virtuous example of the proper dialogue to reach a compromise between safety and conservation. In particular, this pilot site intends to promote a new perspective to reverse the standard logic of total replacement of the structural elements, as usually do when these are not strictly involved in connoting the external image of the building. A more significant design effort can usefully address the conservation of most of the recoverable timber elements, assuming them as a material document of historical techniques.

2. KNOWLEDGE, SURVEY, DIAGNOSTICS

First of all, the correct design of the structural recovery of a historic construction must start from the reconstruction of the building phases, the geometric survey, and non-invasive or micro-invasive diagnostics for the characterization of the materials. The structure survey was carried out by Prof. Andrea Lingua and his team (Politecnico di Torino) by laser scanning with the return of a point cloud of the timber structures (after remove of noisy points, Fig. 2). The remarkable technology allowed determining with precision the geometry of the structure and the dimensions of all the elements, despite the structure itself being apparently disordered. This work enabled successive accurate structural modeling.

The structural scheme consists of the following sequence of mutually supportive elements:

- two main trusses (North and South), resting on the perimeter walls and characterized by tie beam partially resting on the ribs of the vault (red in Fig. 3) and rafters (green in Fig. 3), worked with a *half-lap* joint at the ridge;
- quay beam on the crossing of the rafters (yellow in Fig. 3), characterized by two overlapping elements;
- two cantonal beams (blue in Fig. 3) resting on the perimeter walls through joists;
- ridge beam (purple in Fig. 3), resting on the West side on the masonry. On the East side, the ridge beam is supported by recent props and located below the intersection with the two cantonal beams, with partial support on one of the rafters (transparent violet in Fig. 3).

The rafters of the trusses on the East side also support a cross beam on the East slope. This cross beam supports the rafters of the same roof, and at the cantilevered final part, also similar cross beams on the North and South slopes (all the cross beams are highlighted in dark yellow in Fig. 3). The structure is completed by minor rafters, with sections varying from 16 cm x 16 cm to 12 cm x 12 cm, including some strongly round sections. The arrangement of the minor rafters is laid out on all the slopes with orientation “hut” converging towards the ridge (Fig. 7). These minor rafters lie with fan-shaped planimetric distribution to support the thiny stone slabs covering. In the Western part towards the chapel’s entrance, the fan-shaped distribution of the rafters is arranged to connect the different heights of the main ridge and the ridge of the frontal tympanum.

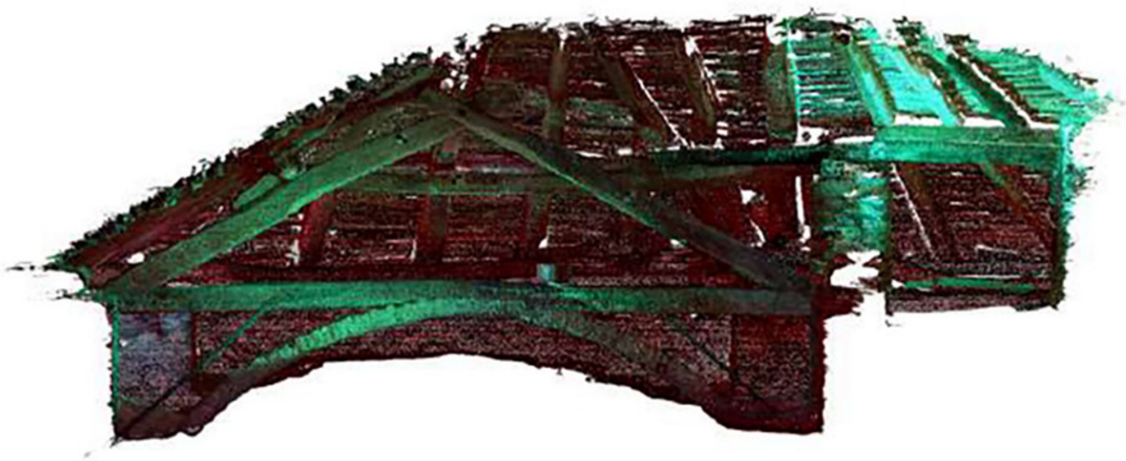

Fig. 2. *Survey image by the laser scanner.*

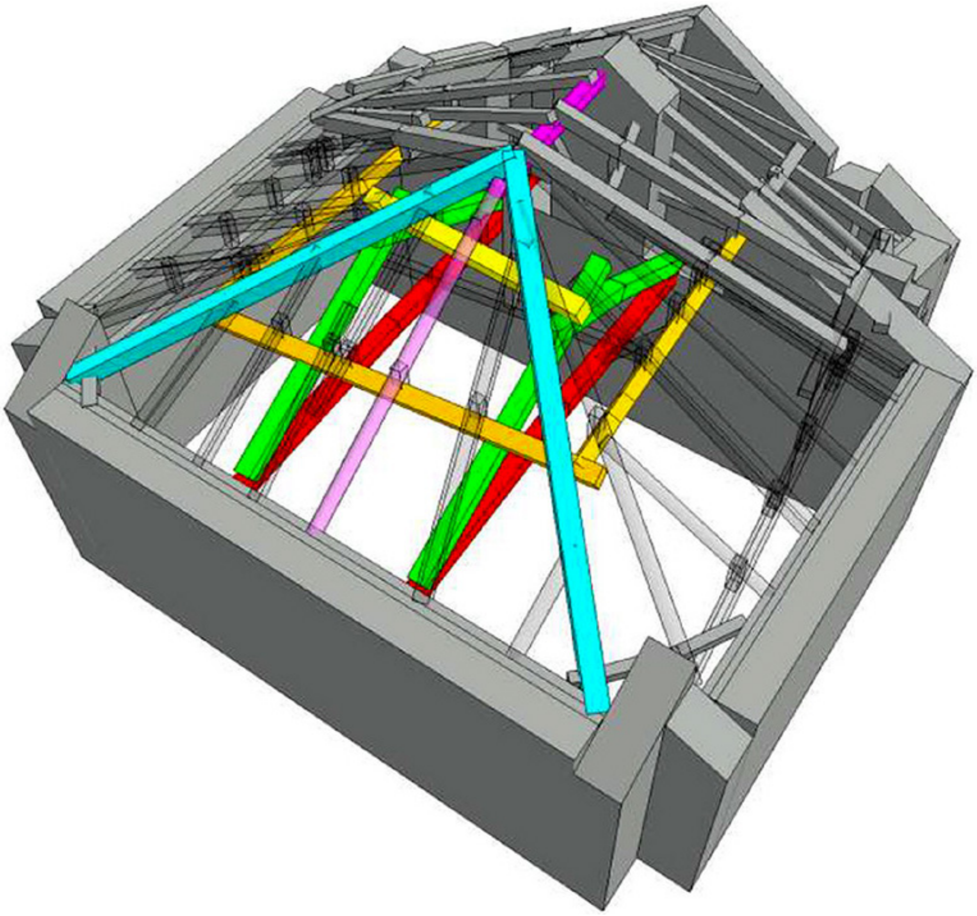

Fig. 3. *The structural frame of existing timber elements.*

2.1. CONSERVATION STATUS OF THE MAIN WOOD ELEMENTS

The timber structures were investigated using a resistographic test conducted at the final part of the elements, repeating the test at a short distance when a potential degradation has been identified. The most significant degradation was found near the support of the truss, (corresponding to point 1 in Fig. 4), strongly compromised by humidity and infiltrations of rain from the roof covering (stone slabs).

Both trusses are made up of timber tie beams, section 20 cm x 20 cm, resting on the East and West walls and timber rafters of a similar section (Fig. 5a). The connections of the rafters on the tie beams are arranged as common practice, with the support surface oriented according to the bisector of the angle of incidence (Fig. 5b). It should be noted that the tie beams of the trusses have metal elements inserted into the masonry walls and connected to anchoring brackets on the external sides, thus forming a metallic tie of the ribs of the masonry vault (Fig. 5a). Both tie beams rest on the extrados of the vaults and are slightly curved (deformation just under 10 cm), with the supports at lower altitudes than the center lines (Fig. 5c). The top of the rafters has a *half-lap* coupling connection, therefore without the presence of the classic connection by the king post, with both rafters continuing in the complete section beyond the coupling area (Fig. 5d). The North truss has the supporting section of the tie beam totally degraded, corresponding on the East side (Fig. 5b), with a partial impairment of the coupling surface of the corresponding rafter. The South truss has conditions of partial degradation of the tie beam in the middle section and at the East final part. The East rafter presents conditions of partial deterioration in the top portion. The trusses support a quay beam on the fork generated by the crossing of the rafters (Fig. 5d). This beam is made up of the overlap of two beams in order to reach the correct support level for the cantonal beams and the

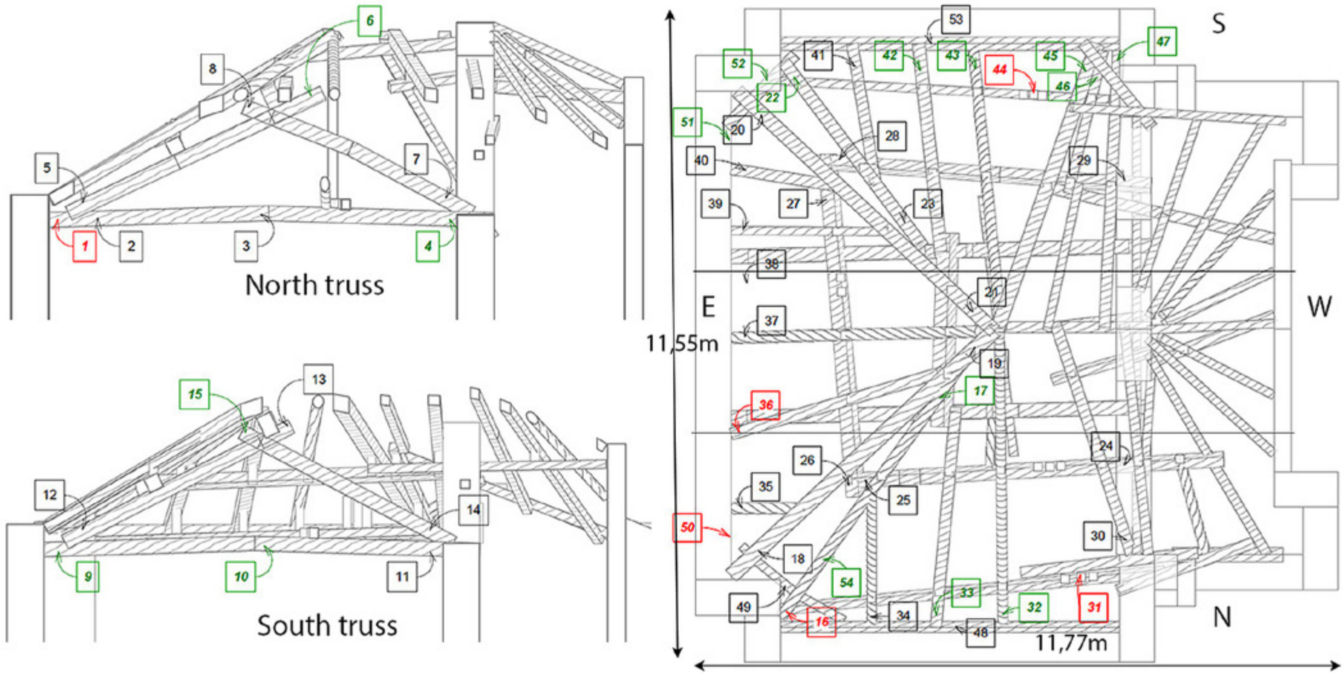

Fig. 4. *Results of resistographic tests carried out on wood structures: in black, the points in good conservation, in green, those corresponding to slight or moderate degradation, in red, those corresponding to advanced degradation.*

Fig. 5. *(a) North truss; (b) detail of the tie beam-rafter connection, in evident degradation inside the masonry support; (c) tie beam rests on the extrados of the vaults; (d) detail of a half-lap coupling connection.*

intermediate rafters of the East slope. The connection of the tops with the quay beam and with the rafters of the North and South slopes guarantees the overturning stability of the trusses.

The two cantonal beams, with 20 cm x 20 cm sections, rest at the bottom on the East masonry near the North and South corners and high on the quay beam, continuing cantilevered until you reach the peak (Fig. 6a).

By observing the conformation of the trusses' rafters and the position of the ridge beam, it would have been possible to hypothesize the presence of a beam resting on the final part of the rafters, supporting the ridge beam (Fig. 6b). To a more careful analysis, it has been understood, instead, that such workmanship corresponds to an early construction phase of the building still without the forepart on the West side, resulting in the symmetrical roof pitches on the East and West side.

The central rafter of the eastern slope of the roof converges with the two cantonal beams in the same position. The ridge beam is in this position of convergence below the converging beams without finding any support. Currently, it is supported by two props of apparent recent insertion, one inclined and resting in the inner masonry on the western side. The other is vertical and rests on a crossbar resting on the tie beams of the trusses (Fig. 6c).

On the eastern layer, a cross beam (20 cm x 20 cm) is resting on the rafters of the two main trusses. The cross beam of the northern layer, with section 16 cm x 16 cm, appears carefully chosen with a deformation that facilitates the support on the main cross-section of the opposite façade.

With regard to wooden frame supporting the stone roof covering, integrative elements are paired to some minor rafters degraded, especially in the terminal section. Along the entire perimeter of the roof, on the top of the walls, there are timber quay elements connected by means of wood processing or by partial overlapping, completed in the corners by diagonally arranged elements.

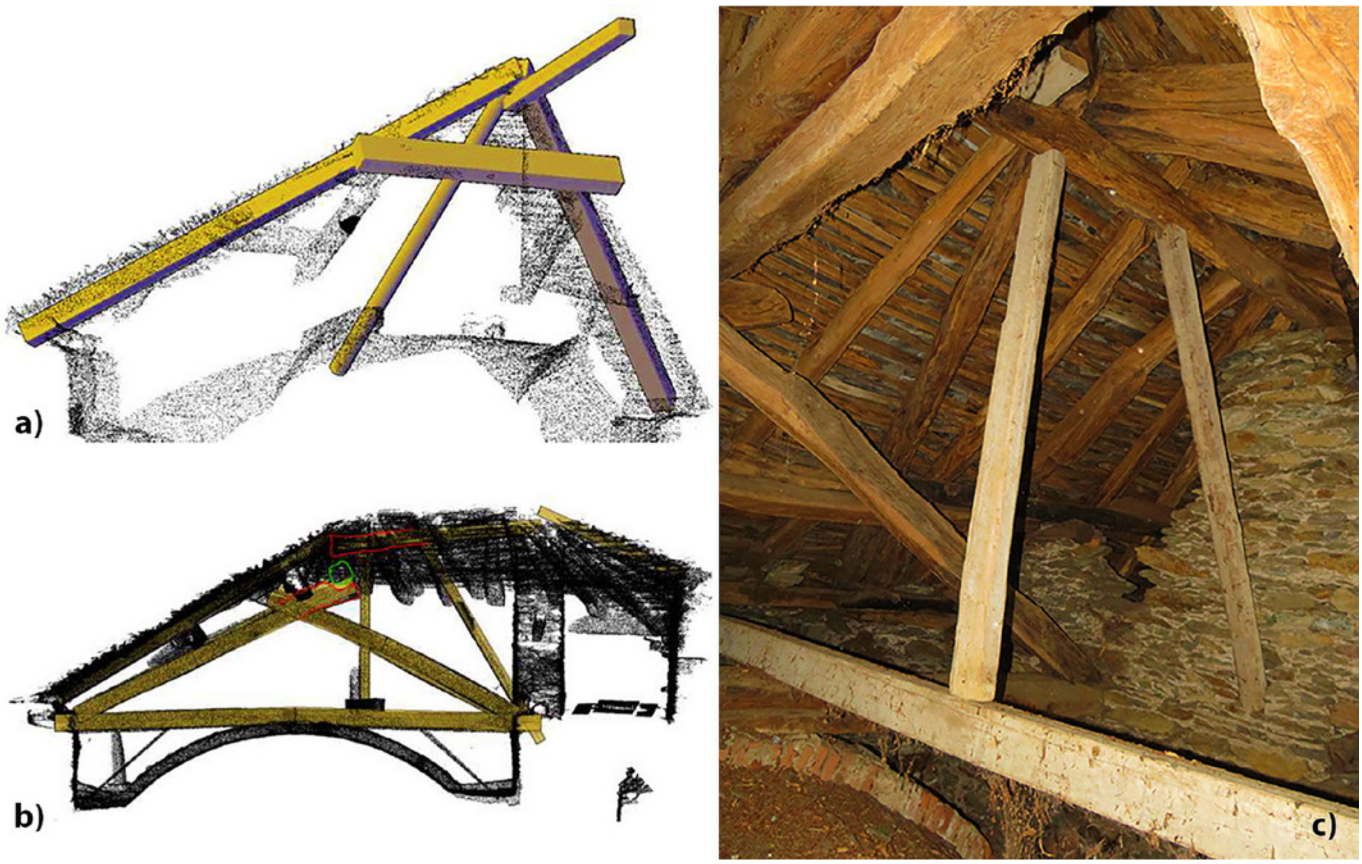

Fig. 6. *(a) Laser scanner survey of the roof area, including the two cantonal beams; (b) hypothesis of the original configuration of the ridge beam; (c) props to support the ridge beam.*

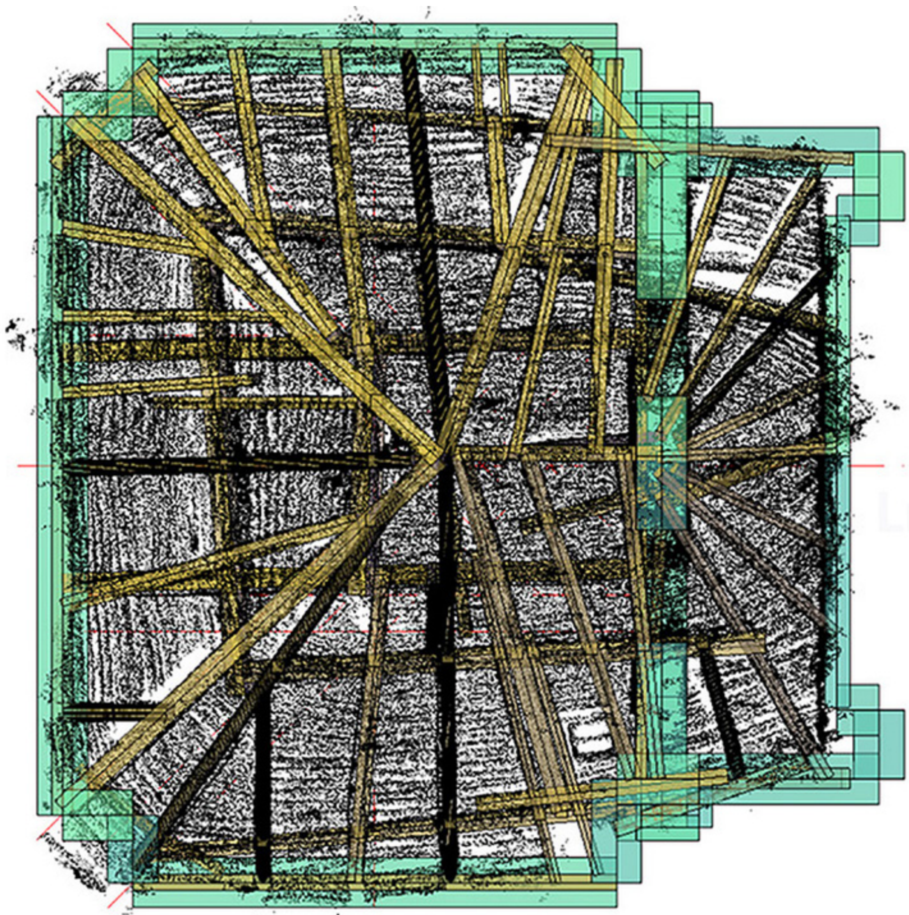

Fig. 7. *Arrangement of the minor rafters in the "hut" roof schema.*

3. STRUCTURAL VERIFICATION OF TIMBER ELEMENTS

A three-dimensional structural model, carried out by finite element software, was made with the positioning of all the wooden elements in perfect match with what was detected by a cloud of points of the survey by the laser scanner. The bonds between the overlapping wooden elements were modeled by inserting vertical connection elements to simulate the reciprocal support connection. The structural modeling has taken into account all integrative elements, resulting in the transfer of a significant portion of the weight of the stone-roof covering on the supporting timber elements. This model allowed the evaluation of the thrusts of the two trusses on their chains and the horizontal forces transmitted by rafters to the quay elements. With separate modeling, the individual components were taken into account to compare the stresses with models that are much simpler and easy to control.

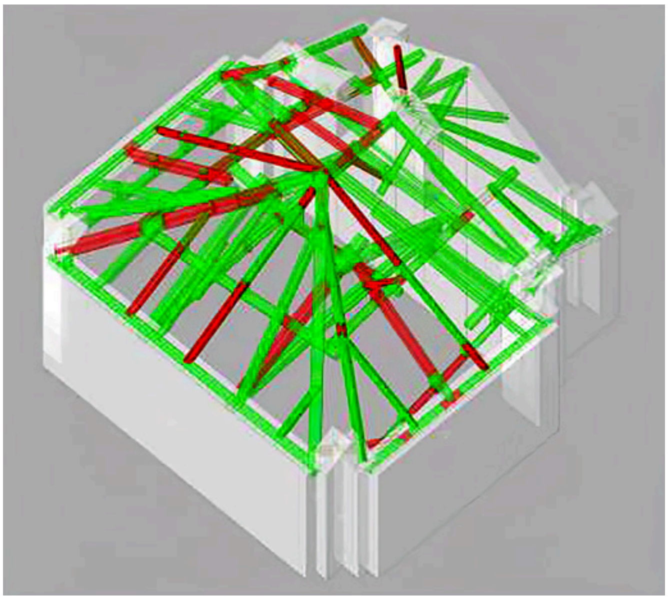

Fig. 8. *Results of static verifications for the roof elements.*

The analyses covered only static load combinations by Italian technical standards [1, 2]. Therefore, the loads considered have the following values: 0.20 kN/m^2 for the actual weight of the timber structure of the roof; 2.8 kN/m^2 for the weight of the roof covering stone (3 layers of slabs, 3 cm thick each one); 1.5 kN/m^2 for the snow overload, for a total of 4.5 kN/m^2. The checks were carried out considering chestnut wood, with the D24 to D18 resistance class [14]. The graphic representation of the verifications of the timber elements is shown in Figure 8, in which the elements with suitable dimensions are represented in green, while those with inadequate sizes are in red.

Since the recovery project has provided only a partial replacement of the roof structure, given the complexity of the geometric distribution of the beams, it was not considered appropriate to insert any top ring beam, even with a compatible masonry technique, so as not to remove the entire scheme of the minor rafters. In fact, the structural work has prioritized the static safety of the original timber structures of the roof, improving, first of all, the connections between the elements, although with a view to reducing the seismic risk in the future. For these reasons, the analysis of seismic vulnerabilities has not yet been carried out in depth. However, further strengthening work of seismic safety can be undertaken later, always favoring punctual reinforcements [15, 16].

4. THE RESTORATION AND STRUCTURAL RECOVERY PROJECT

The restoration project has provided for the conservation and restoration of the elements most characterizing the roof, particularly the two trusses and one main cantonal beam. Through the preliminary surveys, it was possible to identify the undersized or degraded wooden elements, on which the subsequent structural analysis revealed excessive stresses, in particular in some elements spaced by an excessive distance. Therefore, it has been planned to preserve the less affected elements, replace newly or degraded substitute elements, and provide a repositioning for some of them (providing a closer distance where it was necessary) in order to ensure a better distribution of the weight roof covering over them. The adjustments were very modest and only due to the search for the best mutual positioning.

Fig. 9. *(a) Positioning of the timber prosthesis; (b) the timber-timber prosthesis performed.*

Also, it has been planned to replace all quay beams on the North, East, and South slopes and the angular elements, preserving the quay beam incorporated in the West masonry while still ensuring the connection with the new elements of the other layers. The replacement of the quay beams took place by the slight lifting of the minor rafters acting in such a way as not to unbalance the entire structure, prop it up and fan it to ensure the stability of the whole. Moreover was planned to replace the ridge beam and add two cross beams parallel to the same beam, creating a frame/scheme with a more precise structural concept. The supporting knot of the South truss, compromised by the material degradation, was reinforced with a conservative solution by means of timber-wood prosthesis inserted in contrast with clamping screws, without resorting to epoxy resin prosthesis of undoubted/unproven compatibility (Fig. 9). The main connection was made with screws passing from the extrados rafter to the intrados of the tie beam and between the integrative transverse element and the tie beam.

During disassembly, the timber elements were separated by distinguishing elements in good conservation conditions from degraded elements to be eliminated (Fig. 10a). The separation of the elements was submitted to the Work Director for approval. The direction of the work was carried out by eng. Giovanni Vercelli, with the support of the technicians of the Ente di Gestione dei Sacri Monti. Recoverable elements have been cleaned and treated to improve their conservation (Fig. 10b, c). During the repositioning phase, the timber elements were remodeled in order to adapt to the geometry of the bearing structure, alternating the recovery elements with the replacement elements in chestnut wood (Fig. 10a, b).

Fig. 10. *(a) Placement of new timber elements alongside the original ones cleaned up; (b) integration of the new quay beams into the original structural scheme; (c) cleaning and static improvement of the area around the ridge beam; (d) reconstruction of the original stone roof covering.*

The existing stone roof covering has been relocated following the traditional construction techniques (Fig. 10d), replacing the minor support degraded elements and adapting to the new stone slabs.

5. CONCLUSIONS

The roof recovery in the XVI Chapel at the Sacro Monte of Orta (Italy) contemplated critical phases of study and preliminary analysis. These have allowed not to follow a generic road of total replacement of the roof, enhancing the original elements still statically valid. The assessment of the structural safety of a historic building must be carefully interpreted, also calibrated toward the preservation of the original construction technique. Safety and conservation are two important requirements that Italian technical standards can enhance and bring together. The designer must demonstrate the suitable sensitivity to set good static and seismic improvements of the ancient timber structures without compromising their conservation, especially concerning the original construction techniques. The original structural schemes are to be conserved and improved statically and seismically using additional elements in wood or with steel reinforcements.

This recovery building site has been able to enhance a methodological path that has not provided *a priori* total replacements or invasive interventions on the existing building. The design process has been characterized by many technical reflections that have led to the joint effort to preserve and consolidate rather than remove. This methodological approach is, in fact, based on the concept of increased safety made for subsequent steps and interventions, especially in the context of monumental assets.

The historic timber structures represent an inestimable architectural heritage made of architectural history and construction techniques of the past that require simultaneous conservation of authentic elements, enhancement of original static *schema*, and structural safety improvement. The result of the work was excellent in terms of balance in conservation and improvement of the static safety of the timber elements of the roof, also safeguarding the original composition of the stone covering. Moreover, it represents a referring example for the maintenance interventions on similar historic buildings widespread on the territory in the same cultural context.

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Authors contribution

Conceptualisation, MZ, AG, SF, GV; methodology, MZ, AG, SF; software and structural modeling, AG and GV; validation, MZ; investigation, AG, MZ, GV, SF; technical solution for strengthening AG, GV; writing – original draft preparation, AG; writing – review and editing, MZ, AG, SF; supervision, MZ.

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