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Design and modelling tools for timber-based seismic retrofitting: from research to practice

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Abstract

Reversible retrofitting techniques for protecting existing or historical buildings against seismic events have found increasing application in the recent years. In particular, the use of wood-based strengthening solutions for both timber and masonry structures has shown promising results in terms of reversibility, compatibility, lightness, sustainability, and effectiveness. With reference to existing timber floors, an excellent method to enhance their seismic response is the fastening of an overlay of plywood panels to the existing sheathing, an intervention that greatly improves in-plane strength, stiffness, and energy dissipation. In order to promote the use of this retrofitting method in practice, calculation tools supporting the design and modelling of timber diaphragms strengthened with plywood panels, have been developed. As a result of a fruitful synergy between academic research and professional engineering, this work presents relevant recent examples of application of the developed calculation tools in the seismic retrofitting of timber diaphragms in existing buildings. Three significant case-study buildings are examined: two masonry churches with monumental timber roofs, and an ancient sawmill with a mixed timber-masonry structure, all located in the province of Brescia (Italy). The developed tools allowed to conduct parametric analyses to calibrate the best retrofitting strategy, and to analyse the additional benefits of the plywood-based retrofitting interventions, especially in terms of hysteretic energy dissipation, affordability, and cost- and execution-effectiveness. This work can contribute to the promotion of timber-based techniques in the combined structural, seismic, and conservation upgrading of existing buildings belonging to the architectural heritage of seismic-prone countries.

Keywords: Timber floors; Plywood; Existing buildings; Architectural conservation; Seismic retrofitting

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1. Introduction

Existing or historical buildings that are part of the architectural heritage of several countries, often feature masonry walls as vertical loadbearing structural components, and timber floors or roofs as horizontal elements. With reference to the Italian context, these building typologies are very frequent, and have highlighted significant vulnerabilities from the seismic point of view, as proved by several local or global collapses observed after recent earthquakes (Indirli et al. 2012, Lagomarsino 2012, Penna et al. 2019). The poor characteristics of masonry walls, the lack of adequate connections among vertical and horizontal structural components, as well as the flexibility and insufficient capability of timber floors to transfer and redistribute seismic loads, can be identified as the main causes of such collapses. Hence, the improvement of these characteristics is essential for preserving monumental constructions and the architectural heritage in general, by limiting as much as possible the structural damage induced by earthquakes.

However, when designing seismic retrofitting methods for such buildings, their historical value has to be taken into account as well. The selected interventions have thus to be reversible, not invasive, and enable the architectural conservation of these structures. In this context, timber-based techniques constitute a promising, effective opportunity for reversible seismic strengthening and restoration of existing buildings (Branco et al. 2015, Brignola et al. 2012, Dizhur et al. 2018, Giongo et al. 2013, Gubana 2015, Gubana and Melotto 2018, Lin and LaFave 2012, Mirra et al. 2020, Mirra et al. 2022, Moreira et al. 2012, Peralta et al. 2004, Wilson et al. 2014). With reference to the improvement of the response of timber floors to earthquakes, research studies on wood-based retrofitting techniques such as the overlay of cross-laminated timber (Branco et al. 2015), oriented strand board (Gubana and Melotto 2018), or plywood panels (Brignola et al. 2012, Giongo et al. 2013, Giuriani and Marini 2008, Mirra et al. 2020, Mirra et al. 2021a,b,c, Mirra et al. 2024, Peralta et al. 2004, Wilson et al. 2014), demonstrated the excellent performance and high potential of these strengthening methods. In particular, an overlay of plywood panels fastened around their perimeter to the existing sheathing can greatly increase not only the in-plane strength and stiffness of a wooden floor, but also its energy dissipation, providing additional benefits for the whole masonry building (Gubana and Melotto 2018, Mirra and Ravenshorst 2021,2022, Wilson et al. 2014). Based on these advantages, to promote timber-based seismic retrofitting techniques and facilitate the adoption and application of this strengthening method among professional engineers, a set of design and modelling tools has been developed in a companion paper (Mirra 2024a). This collection of tools enables professionals to adopt an integrated approach for the design and modelling of plywood-retrofitted floors, and can be downloaded from the *4TU* data repository (4TU.ResearchData 2024).

As a result of a fruitful synergy between academic research and professional engineering, this work presents relevant recent examples of application of the developed calculation tools, briefly recalled in Section 2, for the seismic retrofitting of timber diaphragms in existing buildings. Three significant case-studies are examined: two masonry churches with monumental timber roofs (Sections 3 and 4), and an ancient sawmill with a mixed timber-masonry structure (Section 5), all located in the province of Brescia, Italy (Fig. 1).

Fig. 1. Location and view of the three analysed case-study buildings in the Province of Brescia, Italy.

2. Developed design and modelling tools

The developed collection of tools, presented in detail in a companion paper (Mirra 2024a), enables the design and detailed numerical modelling of plywood-based seismic retrofitting interventions on existing timber diaphragms. First, a calculation tool (*ApPlyWood*) was implemented, allowing users to obtain an estimate of strength, stiffness, and dissipative properties of diaphragms retrofitted with plywood panels, as well as to visualize their nonlinear, cyclic response. Second, a user-supplied subroutine (*SimPlyWood*) for DIANA FEA software (Ferreira 2023) was implemented, enabling the numerical simulation of the in-plane seismic response of the retrofitted diaphragms by means of a macro-element modelling strategy. The adopted integrated approach can be utilized to design and effectively simulate the nonlinear seismic behaviour of the diaphragms (Mirra 2024a, b). In this way, it is possible to obtain preliminary indications and calibrate retrofitting interventions according to the specific needs of a building, relying on the adaptability and versatility of the plywood-based strengthening method.

In the following, the use of these tools in support of the seismic upgrading and architectural conservation of three historic buildings belonging to the architectural heritage of the Province of Brescia, is presented, along with the practical benefits in terms of the design, modelling, execution, and structural response of timber-based retrofitted floors.

3. First case study: timber-based retrofit of the wooden roof in St. Andrew’s church (Ceto, Brescia, Italy)

The Church of Ceto (Fig. 2a), built 1708–26, is a stone masonry building consisting of a single vaulted nave covered with a roof entirely consisting of wooden structural elements (spruce and larch). Overall, the case-study church did not present issues from the static structural point of view. Several cracks and detachments of material could be observed from the first inspection, but these only involved the finishing layer, and had been caused by the chemical and thermo-hygrometric incompatibility between stone masonry and cement plaster, here improperly applied in past restoration works. The existing metal ties were in good state and well restrained to the walls, and the masonry structural elements appeared to be well dimensioned and constructed (Mirra et al. 2023a,b).

The wooden roof structure was found in fair state of conservation, but connections among its members and the walls were either absent or not effective. Since in this situation the roof would not be able to act as a diaphragm, absorbing the seismic actions and redistributing them to the masonry walls, timber-based seismic retrofitting interventions were designed and applied to the existing roof structure. The main retrofitting intervention consisted of transforming the existing roof in a diaphragm. To this end, an overlay of 30-mm-thick plywood panels fastened to the existing sheathing with 4×60 mm nails at 80 mm spacing, was realized (Fig. 2b-c). Aided by *ApPlyWood* calculation tool, it was possible to design and quantify the main properties of the retrofitted roof: overall, the diaphragm had an in-plane shear strength of 275 kN at 35 mm displacement, and an initial stiffness of 44 kN/mm (Fig. 2d, Mirra et al. 2023a).

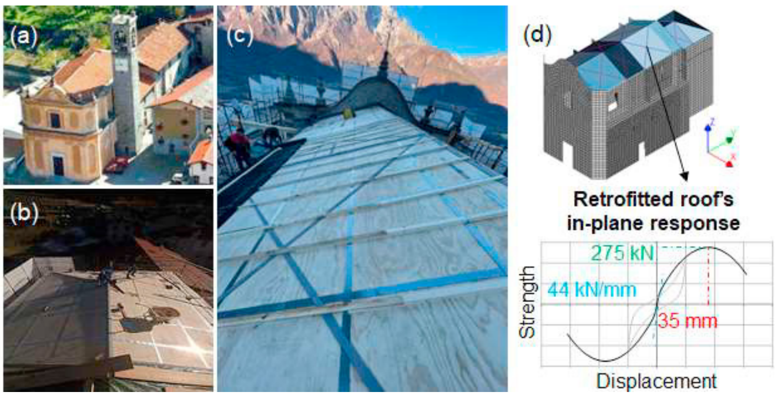


Fig. 2. First case-study building: (a) view of the church of St. Andrew, Ceto; (b),(c) plywood-based seismic retrofitting intervention on the roof designed with the support of *ApPlyWood* calculation tool; (d) numerical model in DIANA FEA including the full nonlinear response of the roof diaphragm, implemented in the user-supplied subroutine *SimPlyWood*.

The applied solution enables the adequate transfer of seismic forces and the development of the box behaviour of the construction, but without significantly changing the stiffness of the entire building. Besides, this type of diaphragm can also potentially act as dissipative element, absorbing part of the energy imparted by the earthquake by means of the yielding of the fasteners connecting planks and plywood panels (Mirra et al. 2023a). In correspondence of the walls, the perimeter of the plywood overlay was surrounded by steel plates to create adequate connections to the existing masonry through M20 anchor bars, enabling the transfer of shear and tensile stresses.

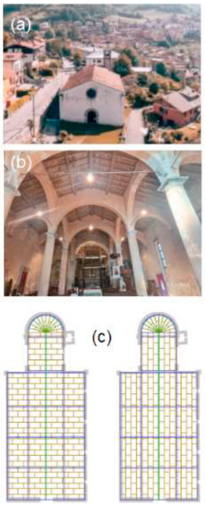
In order to verify the improvement in seismic response of the church, several numerical models, reported in detail in Mirra et al. (2023a), were created in finite element software *Aedes.PCM* (AEDES 2024) and *DIANA FEA* (Ferreira 2023). In *DIANA FEA*, the global nonlinear cyclic response of the plywood-retrofitted roof diaphragm was simulated with a macro-element modelling strategy, adopting the user-supplied subroutine in *SimPlyWood* package (Fig. 2d, Mirra et al. 2023a). In this way, it was possible to capture the beneficial energy dissipation provided by the yielding of the fasteners in the plywood panels overlay, associated to an equivalent damping ratio of 0.12-0.13 for this case (Mirra et al. 2023a), beneficially reducing the actions transferred to masonry walls. Before the retrofit, overturning of the façade could take place already for peak ground acceleration (PGA) of 0.03g (Mirra et al. 2023b), and the wooden roof structure would not have been able to develop appreciable energy dissipation due to the prior development of this local collapse mechanism. On the contrary, after retrofitting and effectively connecting the roof to the walls, the results from numerical simulations proved that the church could potentially survive the on-site design earthquake (PGA = 0.08g), also because of the hysteretic energy activated in the roof (Mirra et al. 2023a).

4. Second case study: timber-based retrofit of the wooden roof in St. Rocco's church (Collio, Brescia, Italy)

The church of San Rocco is an ancient building located upstream of Collio, a village in Valle Trompia, province of Brescia, Italy (Fig. 3a-b). The church, whose architectural layout is typical for the roman-gothic style, was built between the 15th and 16th century, and has been listed as national monument since 1912. The structure has been subjected to an extensive series of strengthening interventions during the past century, with specific regard to the stability of the facade and the longitudinal walls. These had been compromised over time by the ineffective action of metal ties, which led to heavy disconnections and settlements among the walls, highlighted by vertical cracks (Gerardini et al. 2024). These failure mechanisms have been stabilised in the 1990s, by partly replacing the façade ties. Furthermore, the particular configuration of this structure, typical of the gothic-roman churches, has an intrinsic seismic vulnerability: the seismic-resistant system is only composed of the perimeter walls of the main body, since the contribution of the transverse arches (Fig. 3b), while constituting a large seismic mass, is not significant in terms of strength (Giuriani et al. 2009).

On this basis, the existing timber roof structure should provide an effective diaphragmatic action, which can be achieved also in this case through in-plane plywood-based strengthening. The raising interest in the preservation of this church in the local community and the crucial role played by the roof in the static and seismic structural response of the building, required a detailed analysis of the possible retrofitting and conservation design strategies. Hence, aided by *ApPlyWood* calculation tool, parametric analyses have been conducted on several options for the timber-based retrofitting of the monumental roof. Considering as reference strengthening system an overlay of plywood panels fastened along their perimeter to the existing roof sheathing, the influence of factors such as orientation and thickness of the panels, type of fasteners and spacing, was investigated (Fig. 3c-d). Furthermore, a price analysis was also performed for all examined configurations, based on locally applied costs (Lombardy, Italy).

Ten variations (A–L, Fig. 3d) in the plywood-based retrofitting intervention on the roof were considered (Gerardini et al. 2024). In all cases, the thickness of the existing sheathing was t_1 = 30 mm and its density ρ_1 = 480 kg/m^3; the plywood panels had width w_2 = 1220 mm and density ρ_2 = 600 kg/m^3. The varying parameters were the plywood thickness (t_2 = 21 or 30 mm) and orientation with respect to the seismic load, and the fasteners' type and spacing (Fig. 3d). In cases A and B, only the typology of the fasteners was changed. Although the diaphragm's strength is similar, configuration B features a halved in-plane displacement, a result in line with previous literature highlighting the stiffer response of screws (Giongo et al. 2014). In the present building, this aspect can be crucial, as reducing the out-of-plane displacement of transverse walls is critical to maintain the stability of the transverse arches. Furthermore, the configuration featuring screws develops also a greater hysteretic damping ratio, due to the anticipated yielding in comparison to that of nails (configuration A).



(d)

	Analysed configurations									
	A	B	C	D	E	F	G	H	I	L
Plywood panels' layout										
Panels' orientation perpendicular to load	■	■	■	■	■	■			■	■
Panels' orientation parallel to load							■	■		
Thickness of the overlay										
Plywood thickness 21 mm	■	■	■	■						
Plywood thickness 30 mm					■	■	■	■	■	■
Fastener type										
4×60 Anker nails	■		■		■		■			
6×60 Anker nails									■	
4×80 screws		■		■		■		■		
6×80 screws										■
Fastener spacing										
80 mm spacing	■	■			■	■	■	■		■
100 mm spacing			■	■					■	
Estimated main design parameters										
In-plane strength (kN)	762	729	609	583	782	779	652	688	1348	1236
In-plane deflection at peak force (mm)	130	78	130	78	130	78	227	144	203	71
Cost of intervention (€/m^2)	48	54	45	50	65	74	65	74	80	82

Fig. 3. Second case-study building: (a) view of the Church of St. Rocco, Collio; (b) interior of the church with highlighted the typical roman-gothic structural system featuring longitudinal and transverse arches; (c) design strategies with a different panels' overlay layout for the seismic retrofitting of the existing timber roof at the basis of the conducted parametric analyses (d), aided by *ApPlyWood* calculation tool.

Configurations C and D are similar to A and B, with only fasteners' spacing changing from 80 to 100 mm. Interestingly, while the peak force reduced by approximately 20%, the costs only decreased by 6%. Cases E and F featured an increased plywood thickness compared to case A and B. The results in terms of force increased only by 2–7%, as can be expected since the diaphragms' strength is mainly given by the plastic behaviour of the applied fasteners. Yet, costs significantly increase by 37–38%. Configurations G and H were characterized by a different panels' layout (parallel to in-plane load), compared to all other cases. The in-plane peak force decreased by 12–17%, because of the lower interlocking effect. However, the in-plane displacement at peak force is almost doubled compared to the previous cases, because of the great number of sliding planes created by the panels' rows in such a large diaphragm (27×17 m^2). Cases I and L show how the fasteners substantially influence the global results: an increase of their diameter greatly improves the in-plane strength. Interestingly, configuration I (with nails) would develop a large strength, but is also characterized by excessive displacements for the structure. Configuration L, on the contrary, limits much more the in-plane displacements up to acceptable values for the case-study structure.

In the case of a seismic improvement intervention according to the Italian Building Code (NTC 2018), where the seismic performance of a building should be increased by 10% relatively to the original situation, the use of the developed calculation tools opens up several possible design strategies. For instance, the diaphragm can be designed to be sufficiently strong and stiff to fully sustain the seismic actions at damage limit state, whereas it could potentially have a slightly lower strength than the expected seismic action on the roof at near-collapse limit state, while still preventing local collapse mechanisms. This strategy would enable the full activation and development of hysteretic energy dissipation (equivalent damping ratios of 13-17%), which is intrinsic in this retrofitting technique (Gerardini et al. 2024).

5. Third case study: timber-based retrofit and conservation of the Venetian sawmill of Vallaro (Brescia, Italy)

The Venetian sawmill of Vallaro (Fig. 4), in the municipality of Vione (Brescia, Italy), was built at the end of the 19th century, and is involved in an extensive restoration project aimed to transform it in a museum. The building can be subdivided in three independent portions A, B, and C (Fig. 4a–c). Portion A (280 m^2, Fig. 4a, c–d) consists of a single-storey timber structure and a stone masonry basement, featuring 50–60 cm thick walls. Both ground floor and roof structures are composed of spruce joists, planks and columns, in poor conditions due to past neglect of the building. Portion B (50 m^2, Fig. 4b, c, h, i) is a two-story stone masonry structure (wall thickness 50–60 cm) with timber floors and roof. Portion C (80 m^2, Fig. 4c, h, l) consists of a prolongation of the roof structure of portion A, and was found in poor conditions as well.

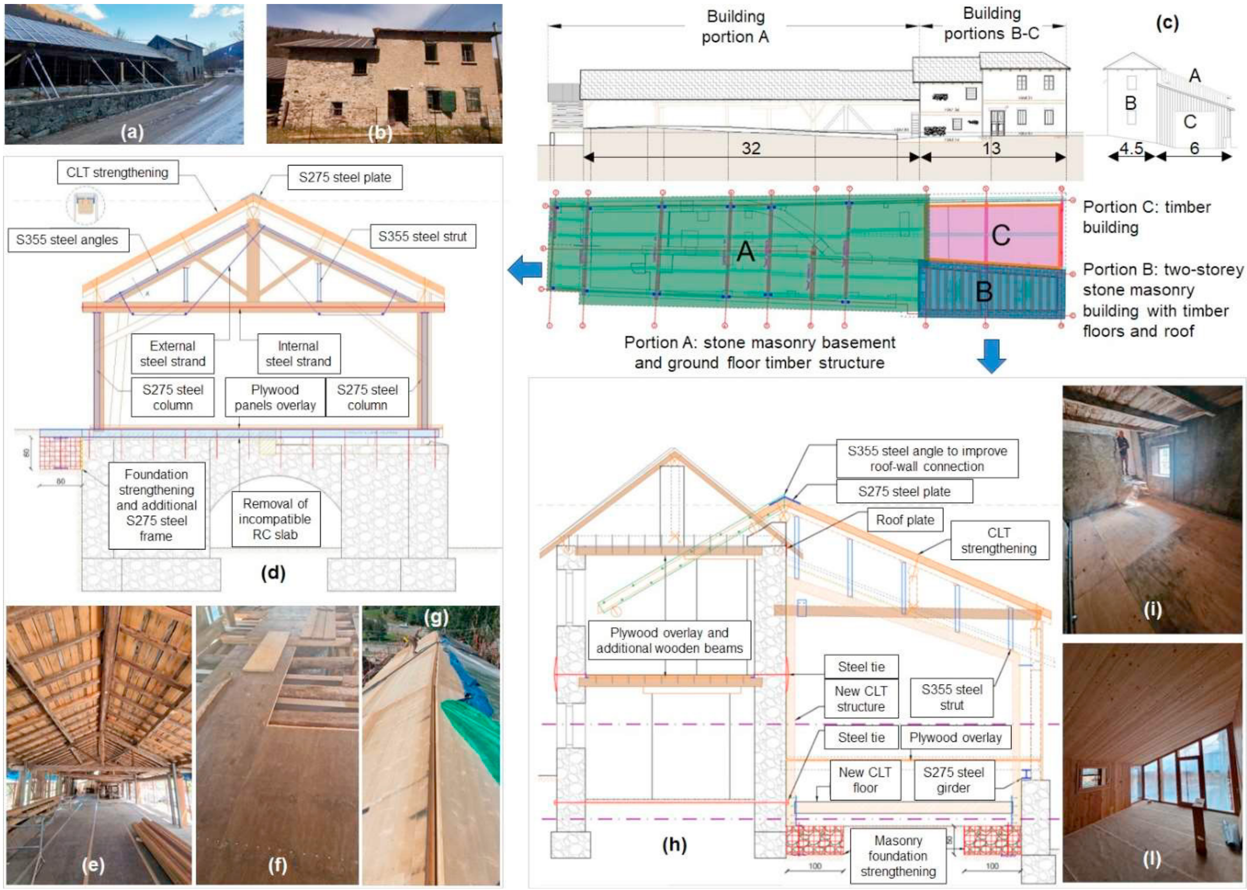


Fig. 4. Third case-study building: views of the timber (a) and masonry (b) portions of the Venetian sawmill of Vallaro; plan and elevations (in m) of the building (c); main interventions applied to portion A (d), with pictures of plywood (e, f) and CLT (g) retrofitting of timber floors and roofs; main interventions applied to portions B-C (h), with pictures of plywood retrofitting of timber floors (i) and of the new CLT structure (l).

The sawmill of Vallaro required several strengthening interventions, not only because of the overall poor conditions of the building, but also in light of the future increased design loads (crowd, snow and wind). Thus, besides the target seismic upgrading, also measures to radically improve the static behaviour of the sawmill were designed. An overview of these interventions is shown in Fig. 4d–l, for all building portions.

For portion A (Fig. 4d), given the low residual load-carrying capacity of the decayed timber columns, newly integrated slender steel elements were designed, along with a new steel frame connected to the strengthened foundations. This not only improves the structural response under vertical loads, but also provides sufficient strength to horizontal actions. In this specific case, in consultation with the local Superintendence, a wood-based solution was not adopted for the columns, because it would have required very massive structural elements, which could partly hide the original appearance of the existing building. Timber-based strengthening solutions were, instead, designed to preserve the wooden floors and roofs and enhance their structural response. Aided by *ApPlyWood* calculation tool, the ground timber floor was strengthened with 30-mm-thick plywood panels and additional wooden elements (Fig. 4e, f). Besides, 12-cm-thick C24 cross laminated timber (CLT) plates, along with additional steel strands were used to improve the static behaviour of the roof (Fig. 4g), and enable its diaphragmatic action, while contemporarily preserving the existing wooden trusses. Also in portion B (Fig. 4h), flexural and in-plane strengthening of the timber floors and roofs was necessary, and was realized by means of new wooden beams and a 21-mm-thick plywood panels overlay (Fig. 4i) fastened on them with 6×120 mm screws at 300 mm spacing. In all cases, effective connections between horizontal and vertical structural elements were designed, including also new steel ties for an improved confinement of the stone masonry. In portion C (Fig. 4h, l), these measures were integrated with the realization of an entirely new prefabricated CLT structure, able to support the existing wooden elements, which showed severe decay and excessive lack of load-carrying capacity. These solutions allowed to preserve as much as possible the original appearance of the sawmill, despite its poor state of conservation; at the same time, the designed interventions also guarantee a safer, renovated environment for hosting a museum.

6. Conclusions

This work has presented the application of several wood-based seismic strengthening techniques on three case-study buildings located in the Province of Brescia, Italy: St. Andrew's church in Ceto, St. Rocco's church in Collio, and the Venetian sawmill of Vallaro in Vione. The use of developed calculation tools presented in a companion paper (Mirra 2024a) in support of design choices and modelling approaches, has been discussed, highlighting the practical benefits of these retrofitting solutions. The timber-based strengthening methods applied to the case-study buildings are all reversible interventions, and compatible with the existing structural members, which could be effectively strengthened and protected: thus, the adopted retrofitting methods also enable the conservation of these buildings. Besides, all floors and roofs can now act as diaphragms and prevent local (out-of-plane) collapses of masonry walls, allowing the buildings to develop a box behaviour against seismic actions. The additional plywood panels overlay fastened to the existing floor planks constitutes a reversible, not invasive intervention, which does not excessively increase mass and stiffness of the floors, and potentially enables additional ductility and energy dissipation, as proved in the conducted numerical analyses. The possibility of quantifying strength, stiffness, displacement capacity and energy dissipation by means of the implemented design and modelling tools, opens up the development and assessment of several retrofitting strategies, in terms of impact on the whole buildings' seismic response, evaluation of costs of materials and execution, (preliminary) structural analyses of the strengthened diaphragms and their numerical simulations.

Besides being efficient in terms of seismic improvement, the designed solutions were particularly appreciated by the Superintendence for Architectural Heritage, as the historical and architectural value of the buildings was preserved. The reasonably low impact on the constructions, linked to a large improvement in their structural properties, is surely a first point of strength of the use of wood-based techniques in these case-study buildings.

Besides, from the perspective of professional engineers, these interventions can be efficiently designed and are particularly affordable. The overlay of plywood panels is a very cost-effective measure, and could be realized within the limited budgets available. This result was possible not only because of lower material costs compared to other solutions, as confirmed by the conducted parametric analyses (Section 4), but also due to the fast and manageable application of the intervention. For instance, for the church of Ceto, the whole plywood panels overlay was fastened to the existing roof by a local building enterprise composed of only three employees within a single working day.

The results obtained within the analysis of these case-study buildings, along with the developed design and modelling tools, contribute to further highlight the benefits of timber-based retrofitting techniques, and to support the research framework promoting their use for the preservation of architectural heritage in seismic-prone countries.

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