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Integration of traditional and advanced seismic protection technologies through timber-based retrofits

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Abstract

The existing building stock in several countries worldwide features masonry structures with timber floors, whose vulnerability to seismic events has been widely documented by academic research as well as by the catastrophic consequences of recent earthquakes. Several seismic retrofits and protection technologies have been explored throughout the years, prioritizing (among others) lightweight interventions, such as timber-based strengthening, or advanced systems involving seismic isolation and vibration control strategies (e.g. inter-story seismic isolation). The use of timber-based retrofits, particularly based on engineered wood panels fastened to existing floors and roofs, has shown to increase the hysteretic energy dissipation of these diaphragms, beneficially reducing seismic shear forces transferred to the walls when the strengthening measure is appropriately designed. Similarly, the seismic isolation of the masses localized at the roof level, can provide a strong reduction in shear loads on the walls, acting as a Tuned Mass Damper for the existing building. On the basis of the described framework, this work examines a case-study archetype masonry building with timber diaphragms: by performing numerical analyses in DIANA FEA software, this study compares (i) the application of timber-based retrofitting solution on the floors and roof, (ii) the use of an additional, superimposed roof structure acting as tuned mass damper with properly calibrated isolators, and (iii) the combination of the two systems, discussing the benefits and applicability of each seismic protection method and their integration with other retrofits, for instance from the energetic and environmental point of view.

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Keywords: Timber-based retrofits; Seismic protection technologies; Inter-storey seismic isolation; Masonry buildings.

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1. Introduction

A significant part of the existing building stock of several countries worldwide consists of masonry structures with timber floors and roofs. With reference to the Italian context, building typologies with these characteristics are very frequent, and have highlighted significant vulnerabilities from the seismic point of view, as demonstrated by several local or global collapses observed after recent earthquakes. The main causes for these failures proved to be 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. In this framework, timber-based techniques have proved to be a viable, reversible option for seismic strengthening and restoration of existing buildings (Gubana 2015, Mirra et al. 2023, Mirra and Ravenshorst 2021). Particularly effective solutions involve the use of engineered wood panels, such as cross-laminated timber (Branco et al. 2015), oriented strand board (Gubana and Melotto 2018), or plywood panels (Peralta et al. 2004, Brignola et al. 2012, Giongo et al. 2013, Wilson et al. 2014, Mirra et al. 2020, Mirra 2024). In particular, the 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 and for locally vulnerable elements, such as the gables (Mirra et al. 2021, Mirra and Ravenshorst 2021, Mirra et al. 2025).

Besides traditional strengthening solutions, more advanced seismic protection technologies for existing buildings have been explored as well. Among them, inter-story isolation systems are increasingly gaining attention as a seismic mitigation technique for both new and existing buildings (Bernardi et al. 2021, 2023a, 2023b, 2023c, Donà et al. 2022). The system employs an isolation layer between two stories, rather than at the base of the building, identifying two independent structures, referred to as substructure (lower structure) and superstructure (upper structure). These structural parts may have different forms, materials and uses, allowing for greater architectural freedom and the realization of sustainable housing solutions in densely populated countries (Donà et al. 2021). The possibility of integrating this system with a (timber) vertical addition on existing buildings is a current subject of research, especially when considering the dynamic effect of higher modes (Sandoli et al. 2025) and the appropriate calibration of the stiffness of the isolators in relation to the degradation of the masonry due to seismic loads (Bernardi et al. 2023b).

By considering an archetype masonry building typical of the Po Valley area in Italy, this work aims at investigating its seismic response through numerical time-history analyses, comparing and combining a traditional timber-based retrofit, i.e. the plywood panel overlay, with an inter-story isolation system located at roof level, acting as tuned mass damper (TMD). Besides the as-built configuration, the following scenarios are examined: (i) the application of timber-based retrofitting solutions on the floors and roof; (ii) the use of an additional, superimposed rigid roof structure acting as TMD with properly calibrated isolators, and as-built floors; (iii) the combination of the two systems, i.e. a TMD rigid roof structure with plywood-retrofitted floors. Benefits and applicability of the interventions and their possible integration with other retrofits, for instance from the energetic and environmental point of view, are discussed as well.

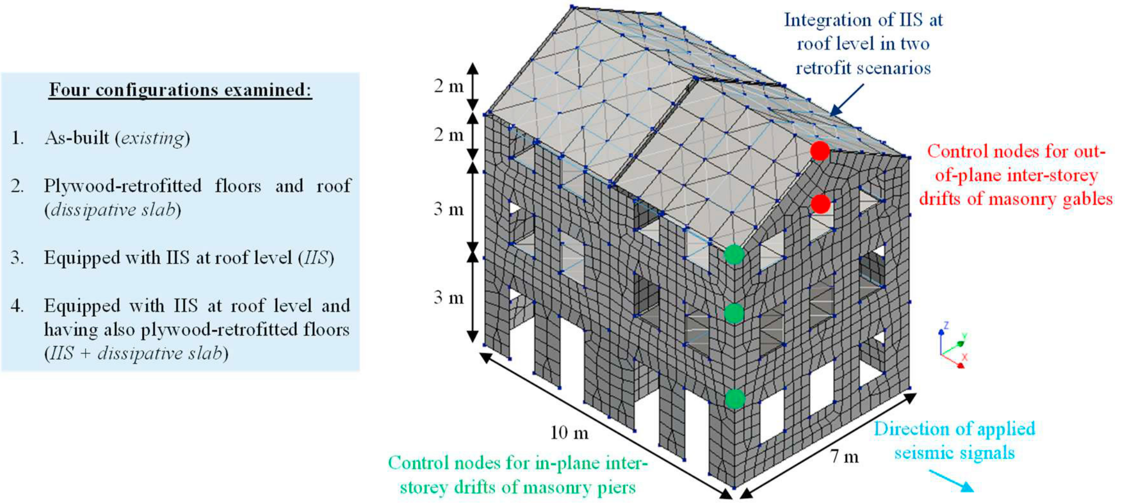
2. Case-study building and examined configurations

The reference case-study building is part of the archetypes examined in a previous work on the effectiveness and optimization of timber-based strengthening techniques (Mirra and Ravenshorst 2021). Besides the as-built configuration and that featuring plywood-retrofitted diaphragms, already investigated in Mirra and Ravenshorst (2021), two other cases were modelled, assuming the same properties for the masonry walls. In the first scenario, a rigid roof acting as TMD was considered, and the floors were kept in their as-built configuration, but were assumed to be effectively connected to the masonry. In the second scenario, the floors were instead retrofitted with an overlay of plywood panels, in addition to the TMD rigid roof.

The building was modelled in finite element software DIANA FEA, adopting the Engineering Masonry Model for the walls, linear elastic orthotropic shell elements for the as-built timber floors and roof, and purposely developed macro-elements (Mirra 2024) for simulating the dissipative in-plane response of plywood-retrofitted diaphragms. In particular, the masonry walls featured an elastic modulus perpendicular to the bed joint of 2500 MPa, shear modulus of 1000 MPa, density of 2000 kg/m^3, compressive strength of 8 MPa, and shear/tensile strength of 0.15 MPa; the as-built timber floors featured an elastic modulus of 10000 MPa and an equivalent shear stiffness of 40 N/mm, while the plywood-retrofitted diaphragms were designed based on the pertaining seismic floor shear (230, 450, and 330 kN from first floor to roof, respectively). For a complete overview of the material properties, the reader is referred to Mirra and Ravenshorst (2021), whereas Fig. 1 shows the examined building.

In both configurations featuring the TMD roof structure, the corresponding isolators at the base of the roof diaphragm were modelled through linear springs with calibrated stiffness and damping, based on the optimized formulation presented in Bernardi et al. (2023a), which is summarized in Fig. 2. By following this procedure, in the configuration where IIS only was applied, each isolator had a stiffness of 762.5 N/mm and a damping of 8.6 Ns/mm, whereas in that where IIS was combined with the dissipative plywood-retrofitted diaphragms at first and second floor, each isolator had a stiffness of 2793.0 N/mm and a damping of 26.8 Ns/mm. In both cases, the ratio between isolated mass of the roof and modal mass of the rest of the substructure (Fig. 2), was approximately 0.06, but the periods of the substructure (0.20 and 0.16 s, respectively) were different because of the different diaphragms' stiffness.

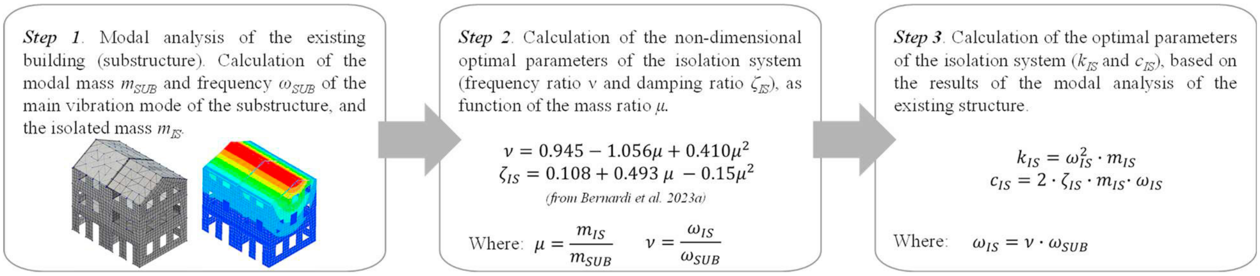
For the as-built configuration and the three retrofits' scenarios, time-history analyses were performed considering a set of seven accelerograms, applied for all cases with the same intensity (≈ 0.4g) that had caused collapse in the as-built configuration (Mirra and Ravenshorst 2021), along the x-direction of Fig. 1, the same used for the optimization of the isolators. This allowed to compare the seismic response of all scenarios for the same ground motion amplitudes, highlighting the specific characteristics of each case.



Four configurations examined:

1. As-built (*existing*)
2. Plywood-retrofitted floors and roof (*dissipative slab*)
3. Equipped with IIS at roof level (*IIS*)
4. Equipped with IIS at roof level and having also plywood-retrofitted floors (*IIS + dissipative slab*)

Fig. 1. Archetype case-study building adopted in this study; the direction of the applied motions and the relevant control nodes are highlighted.



Step 1. Modal analysis of the existing building (substructure). Calculation of the modal mass m_{SUB} and frequency ω_{SUB} of the main vibration mode of the substructure, and the isolated mass m_{IS}.

Step 2. Calculation of the non-dimensional optimal parameters of the isolation system (frequency ratio ν and damping ratio ζ_{IS}), as function of the mass ratio μ.

$$\nu = 0.945 - 1.056\mu + 0.410\mu^2$$
$$\zeta_{IS} = 0.108 + 0.493\,\mu - 0.15\mu^2$$

(from Bernardi et al. 2023a)

Where: $\mu = \frac{m_{IS}}{m_{SUB}}$ $\nu = \frac{\omega_{IS}}{\omega_{SUB}}$

Step 3. Calculation of the optimal parameters of the isolation system (k_{IS} and c_{IS}), based on the results of the modal analysis of the existing structure.

$$k_{IS} = \omega_{IS}^2 \cdot m_{IS}$$
$$c_{IS} = 2 \cdot \zeta_{IS} \cdot m_{IS} \cdot \omega_{IS}$$

Where: $\omega_{IS} = \nu \cdot \omega_{SUB}$

Fig. 2. Procedure for calculation of optimized IIS system, proposed in Bernardi et al. 2023a.

3. Results and discussion

In this section, the results from the performed time-history analyses are compared in terms of average inter-story drifts recorded for both the in-plane loaded piers, and the out-of-plane loaded gables; the crack pattern is also provided for the most damaging signal. The average PGA among the signals is approximately 0.4g, corresponding to the originally recorded failure of the as-built configuration, where out-of-plane collapse of the gables was observed (Mirra and Ravenshorst 2021).

Fig. 3 shows the recorded drifts, both in-plane and out-of-plane, averaged among the seven accelerograms. With regard to the piers (Fig. 3a), it can be noticed that, for the reference PGA at collapse of the existing configuration, none of the other scenarios experienced an in-plane (shear) failure of the walls, since in any case the drift remained below the conventional 0.5% limit. Considering the more traditional scenarios, both the as-built configuration and the plywood-retrofitted case exhibit moderate drifts, with the latter showing the largest value: this result is in line with the fact that the flexible diaphragms of the existing configuration induce a premature out-of-plane failure of the gables, underpinned by their large recorded drift (Fig. 3b), whereas the plywood-retrofitted floors, although dissipative, tend to involve the more desirable and ductile in-plane resisting mechanism of the piers.

The integration of more advanced protection technologies such as the IIS proved to be beneficial, and allowed to reduce the drifts recorded for the former two cases having as-built and plywood-retrofitted diaphragms (Fig. 3a). Of great interest is already the scenario where IIS only is applied, without stiffening the floors: in light of the compact nature of the building and of the optimized calibration in the direction of interest, the isolators located at roof level are able to effectively contrast the in-plane seismic forces, thereby reducing the drift to values even lower than those of the existing scenario. This result comes along with a halved out-of-plane drift in the gables compared to this same case (Fig. 3b). Yet, this value is still relatively large, and can further be reduced by including the plywood-based strengthening: in this case, the in-plane drift is very close to that of the existing scenario, and the lowest out-of-plane drift among all configurations is observed. Furthermore, both drift values are lower than the scenario featuring only dissipative plywood-retrofitted floors, proving the positive integration between these two techniques.

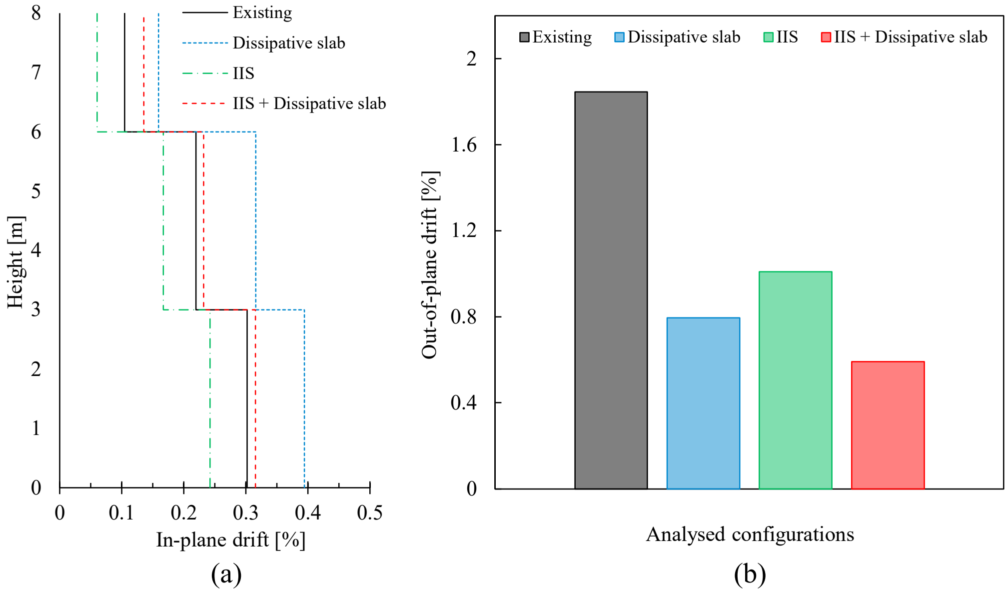


Fig. 3. (a) Inter-story in-plane drift of masonry piers along the building height and (b) inter-story out-of-plane drift of masonry gables for all examined configurations.

These outcomes are further confirmed when examining the crack pattern of the building, reported in Fig. 4 for the most damaging signal among the seven applied to the case-study building. As can be noticed, the existing configuration already shows extensive cracks in the in-plane piers, although the main damaged elements remain the gables, which undergo out-of-plane displacements up to 60 mm, corresponding to drifts of 2% of their height. This local failure mechanism is successfully prevented in the other three examined scenarios, independently of the applied retrofit. However, while the addition of IIS only induces less pronounced in-plane cracks, it still causes some out-of-plane damage; when complemented with the plywood-based retrofitting system the most optimized configuration is obtained, with a more controlled response where out-of-plane and in-plane damage are lower than both the existing scenario and that featuring only the plywood strengthening. These results are promising and indicate the potential effective integration of IIS systems with dissipative timber-based retrofitting techniques. Furthermore, purposely designed roof structures equipped with IIS can combine seismic and energetic upgrading of existing buildings, as well as provide environmental benefits by integrating, for instance, green roof solutions.

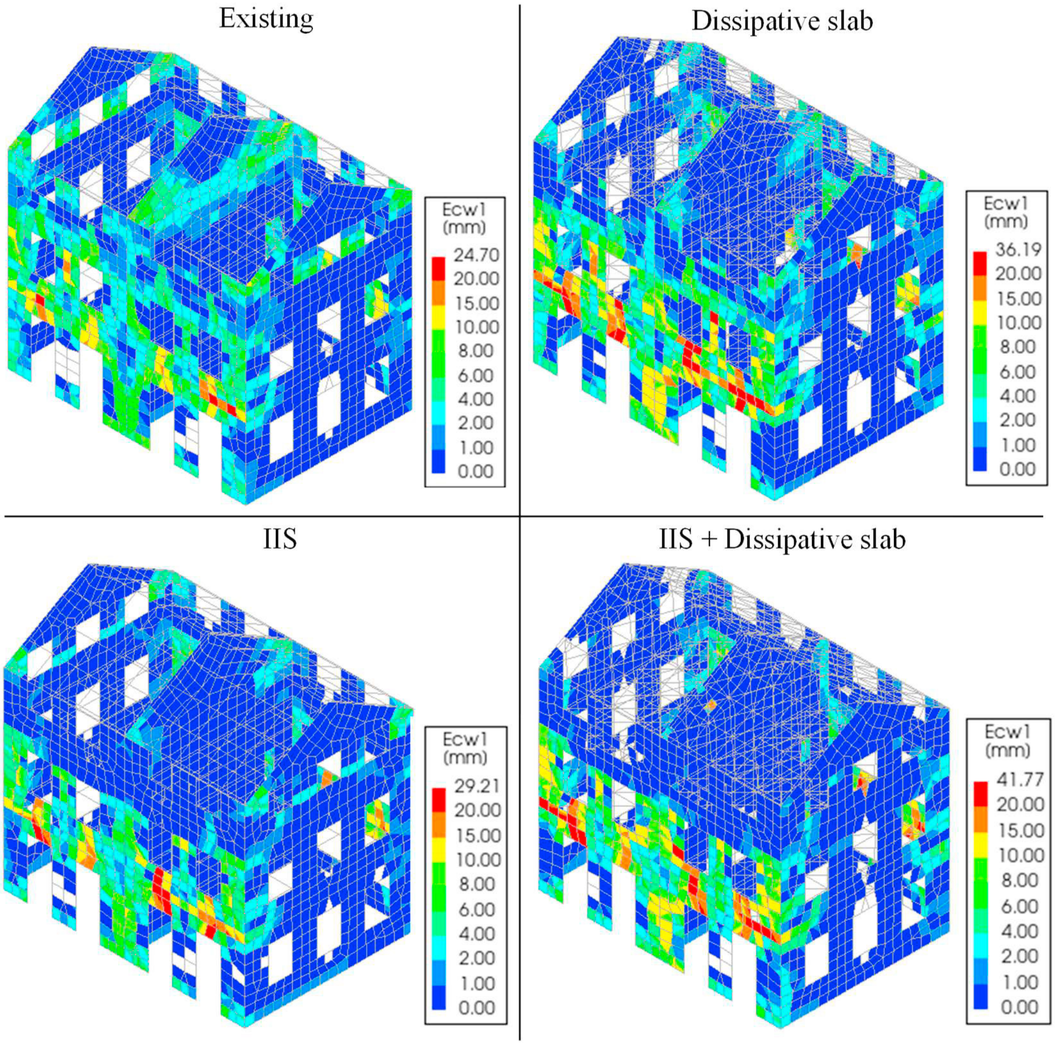


Fig. 4. Crack pattern of the case-study building for the examined configurations under the most damaging earthquake signal, reported in terms of principal crack openings. The same scale is used up to 20 mm, with all values above being displayed in red colour.

4. Conclusions

This study has explored the possibility to combine traditional timber-based seismic strengthening techniques with more advanced seismic protection technologies, such as inter-story isolation systems (IIS). In this work, the potential application of IIS at the roof level of an archetype building has been examined, comparing it with the exiting configuration, a case where only timber-based retrofits are applied, and finally a scenario where the IIS is combined with timber based in-plane strengthening of the floors.

Based on the obtained results from the performed time-history analyses, it can be concluded that (i) the IIS can be successfully optimized in presence of different stiffnesses of the floors, since its installation limits drifts and damage on the building in both the configuration having existing floors and in that featuring retrofitted ones; (ii) the combination of IIS and dissipative timber-based retrofits allows to obtain the most optimal response, in terms of an acceptable in-plane drift on the masonry piers, and a very much reduced out-of-plane drift and damage on the masonry gables, i.e. the most vulnerable portion of the building; (iii) these promising results open up the opportunity to broaden the study by considering simultaneously different earthquake directions and scenarios, and to potentially investigate IIS at roof level integrating seismic, energetic, and/or environmental upgrading of the existing building stock, fostering more resilient urban areas.

References

Bernardi E., Donà M., da Porto F., Tan P., 2021. Investigations on inter-storey seismic isolation as a technique for adding upper Storeys. In: Proceedings of the 8th international conference on computational methods in structural dynamics and earthquake engineering (COMPDYN), Athens, Greece

Bernardi, E., Donà, M., Tan, P., 2023a. Multi-objective optimization of the inter-story isolation system used as a structural TMD. Bulletin of Earthquake Engineering 21, 3041-3065.

Bernardi E., Donà M., Sut S., Saler E., Caprino A., da Porto F., 2023b. Evaluation of the inter-story isolation system applied to an existing masonry school building, Proc. of 9th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2023), Athens, Greece, June 12-14

Bernardi E., Donà M., Ceresara M., Gaspari M., da Porto F., 2023c. Evaluation of the inter-story isolation system applied to an existing RC school building, Proc. of 9th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2023), Athens, Greece, June 12-14

Branco, J. M., Kekeliak, M., Lourenço, P.B., 2015. In-Plane Stiffness of Timber Floors Strengthened with CLT. European Journal of Wood and Wood Products 73, 313-323.

Brignola, A., Pampanin, S., Podestà, S., 2012. Experimental Evaluation of the In-Plane Stiffness of Timber Diaphragms. Earthquake Spectra 28(4), 1–23.

Donà M., Bernardi E., Zonta A., Tan P., Zhou F.L., 2021. Evaluation of optimal FVDs for inter-storey isolation systems based on surrogate performance models. Bull Earthq Eng. https://doi.org/ 10.1007/s10518- 021- 01134-9

Donà M., Bernardi E., Zonta A., Saler E., da Porto F., 2022. Assessment of the inter-story isolation technique applied to an existing school building. In: Proceedings of the Eighth international conference on structural engineering, mechanics and computation (SEMC 2022), Cape Town, South Africa, September 5–7, 2022

Giongo, I., Dizhur, D., Tomasi, R., Ingham, J.M., 2013. In-plane assessment of existing timber diaphragms in URM buildings via quasi-static and dynamic in-situ tests. Advanced Materials Research 778, 495-502.

Gubana, A., 2015. State-of-the-Art Report on high reversible timber to timber strengthening interventions on wooden floors. Construction and Building Materials 97, 25–33.

Gubana, A., Melotto, M., 2018. Experimental tests on wood-based in-plane strengthening solutions for the seismic retrofit of traditional timber floors. Construction and Building Materials 191, 290–299.

Mirra, M., Ravenshorst, G., 2021. Optimizing Seismic Capacity of Existing Masonry Buildings by Retrofitting Timber Floors: Wood-Based Solutions as a Dissipative Alternative to Rigid Concrete Diaphragms. Buildings 11(12), 604.

Mirra, M., Ravenshorst, G., van de Kuilen, J.-W., 2020. Experimental and analytical evaluation of the in-plane behaviour of as-built and strengthened traditional wooden floors. Engineering Structures 211, 110432.

Mirra, M., Ravenshorst, G., van de Kuilen, J.-W., 2021. An analytical model describing the in-plane behaviour of timber diaphragms strengthened with plywood panels. Engineering Structures 235, 112128.

Mirra, M., Gerardini, A., Ghirardelli, S., Ravenshorst, G., van de Kuilen, J.-W., 2023. Combining Architectural Conservation and Seismic Strengthening in the Wood-Based Retrofitting of a Monumental Timber Roof: The Case Study of St. Andrew's Church in Ceto, Brescia, Italy. International Journal of Architectural Heritage, 18(5), 750–770.

Mirra, M., 2024. A set of calculation tools supporting the design, modelling and application of plywood-based seismic retrofitting interventions on timber floors in existing buildings. Structures 63, 106378.

Mirra, M., Damiani, N, Sharma, S., Graziotti, F., Messali, F., 2025. Definition of differential seismic input motions for out-of-plane dynamic testing of unreinforced masonry gable walls considering different roof configurations. Structures 79, 109419.

Peralta, D.F., Bracci, M.J., Hueste, M.B.D., 2004. Seismic Behavior of Wood Diaphragms in Pre-1950s Unreinforced Masonry Buildings. Journal of Structural Engineering 130(12).

Sandoli, A., Vesce, G., Fabbrocino, G., 2025. First insights on the seismic response of existing buildings with timber vertical additions. 10th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2025), Rhodes, Greece.

Wilson, A., Quenneville, P.J.H., Ingham, J.M., 2014. In-plane orthotropic behavior of timber floor diaphragms in unreinforced masonry buildings. Journal of Structural Engineering 140 (1).