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TimberGrid: a novel integrated timber-based solution for the seismic and energy retrofitting of masonry existing buildings

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Abstract

A new timber-based retrofit, called TimberGrid, was proposed within the SAFER-REBUILT project, with the aim of improving both the seismic safety and energy performance of unreinforced masonry (URM) buildings. The system consists of a timber lattice structure composed of studs, rails, and diagonals, connected by screws and carpentry joints. The lattice is anchored to the existing masonry using diffuse dry mechanical point-to-point fasteners (approximately 4-5 per square meter), and connected to the base by means of anchoring devices (e.g., hold downs and angles). This solution, builds on the advantages demonstrated by other timber-based retrofit techniques and emphasizes a rapid and minimally invasive intervention (social sustainability), the use of "less-engineered" timber products (such as solid wood components) from short supply chains (economic sustainability), and improved waste management and materials recyclability (environmental sustainability). Non-linear quasi-static numerical analyses were conducted to optimize the grid layout and joint configurations, providing an initial insight into the effectiveness of the TimberGrid system in enhancing the in-plane wall response. This paper introduces the TimberGrid system and presents the outcomes of simplified and detailed numerical models that are essential for calibrating the full-scale experimental tests planned within the project and for designing the corresponding test set-up.

Keywords: Unreinforced masonry; Timber retrofit; Seismic performance; Energy efficiency; Sustainability.

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1. Introduction

The latent threat of destructive earthquakes, combined with the growing awareness of the need for environmentally sustainable housing, calls for an upgrade of the existing building stock to enhance both its structural safety and energy efficiency. In Mediterranean countries such as Italy, Greece, and Turkey, the high seismic risk is due to the confluence of elevated seismic hazard, dense population (exposure) and an ageing building heritage largely composed of URM buildings vulnerable to lateral loading. From the environmental perspective, buildings sector is one of the main causes of climate change, being responsible for 34% of global energy demand and 37% of CO_2 emissions (Zhang et al., 2024).

To address the dual challenge of reducing seismic vulnerability and lowering carbon emissions, a range of innovative and sustainable timber-based retrofitting techniques have emerged in recent years. Among those, several solutions have been studied for the retrofitting of single walls:

- Strong-backs, involving the installation of vertical timber elements fixed to the interior side of unreinforced masonry (URM) walls using mechanical screws or bolts. This technique is primarily designed to improve out-of-plane seismic performance (Dizhur et al. 2017, Cassol et al. 2021, 2025), but available evidence also indicates beneficial effects on the in-plane response (Maduh et al. 2019).
- CLT panels (Cross-Laminated Timber), attached to the wall surfaces through point-to-point connections, provide a combined in-plane and out-of-plane strengthening effect. These systems have been analyzed by Giongo et al. (2021), Valluzzi et al. (2021), Salvalaggio et al. (2022) and Zanni et al. (2023, 2023).
- Hybrid solutions, which combine strong-backs with different types of timber panels to improve performance while maintaining flexibility. Research in this area includes work by Busselli et al. (2021), Guerrini et al. (2021), Miglietta et al. (2021), Cassol et al. (2024) and Damiani et al. (2024).

These solutions enable the improvement of the structural and energy performance of buildings by integrating structural reinforcement with insulating materials. They also reduce the invasiveness of reinforcement thanks to the lightness and reversibility and minimizes the environmental impact through wood’s inherent sustainability. At the same time, timber-based retrofits offer promising opportunities for further development, particularly in relation to implementation costs, prefabrication, the use of locally sourced materials, and adaptability during construction phases.

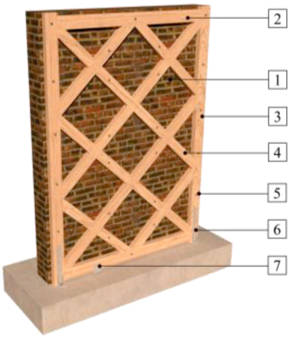
To pursue these advancements, a new timber-based solution called TimberGrid was developed within the SAFER-REBUILT project. The system consists of a timber lattice structure composed of studs, rails and diagonals, which are connected by screws and carpentry joints (see Fig. 1). The lattice is anchored to the existing masonry using diffuse dowel-type fasteners (approximately 4-5 per square meter) and fixed to the foundation using anchoring systems typical of platform-frame constructions (e.g., hold-downs, steel angles).

A numerical study was conducted to assess the system's effectiveness in enhancing lateral resistance using pushover analysis. Various grid configurations were studied to determine the optimal joint layout. Additionally, detailed finite element modeling was used to analyze the behavior of critical nodes in the system.

2. TimberGrid solution

The proposed system consists of softwood timber lattices (C24) connected using mechanical fasteners (e.g., screws) and traditional carpentry joints. Each timber member has a rectangular cross-section with a fixed minor dimension of 60 mm, while the major dimension varies between 100 and 120 mm. This configuration is designed to minimize the invasiveness of the reinforcement while preserving its ability to reinforce masonry walls for in-plane loads. The inclusion of diagonal elements enhances the in-plane shear capacity and increases frame wall stiffness for the post-cracking phase.

The connection between the timber elements is made using timber screws (see Fig. 2.a, Fig. 2.b and Fig. 2.c). Where there is an overlap in the thickness of two continuous elements (e.g., diagonal-diagonal, D-D), a cross-lap joint is adopted.



1) Existing masonry wall
2) Rail [R]
3) Stud [S]
4) Diagonal [D]
5) Timber-to-masonry connection (screw type)
6) Hold-down
7) Angle bracket

Fig. 1. Novel seismic reinforcing technique for URM buildings - TimberGrid

As illustrated in Fig. 2.d, this traditional joining solution allows to limit the use of mechanical connectors by creating a interlocking that ensures effective stress transmission.

The timber grid is connected to the existing masonry using mechanical point-to-point fasteners (Fig. 2.e). Dry dowel-type connectors such as masonry screws efficiently transfer tensile and shear forces, improving in-plane strength while maintaining the reversibility of the retrofit. System effectiveness is ensured by base anchorage, with two hold-downs contrasting rocking and an angle bracket to help transfer shear to the foundation.

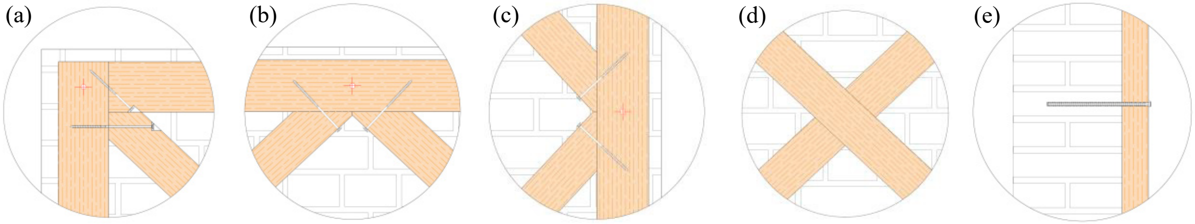


Fig. 2. (a) R-S-D connections, (b) R -D connections, (c) S-D connections, (d) D-D connections and (e) timber-to-masonry connections.

3. Numerical modelling

Four reinforcement configurations were investigated for a two-leaf solid brick masonry wall (2.00 × 2.70 × 0.25 m), as illustrated in Fig. 3. Solution 1 (Fig. 3.a) features a timber frame with 45° diagonal braces for improved shear resistance; the diagonals act as stitches bridging the expected diagonal cracks. Solution 2 (Fig. 3.b) includes only vertical studs and horizontal rails connected with cross-lap joints to evaluate the system without diagonals. Solution 3 (Fig. 3.c) omits cross-lap joints and introduces three vertical studs and diagonal braces to enhance vertical and rocking resistance. Solution 4 (Fig. 3.d) is a hybrid combining elements from the previous configurations.

Preliminary analyses were conducted in SAP2000 (CSI, 2025), while detailed finite element modeling of the critical cross-lap joint was performed using Midas FEA NX (MIDAS IT, 2025).

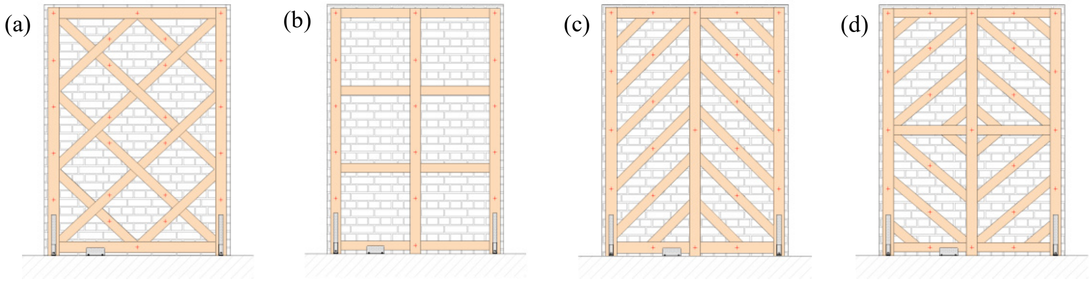


Fig. 3. Reinforcement scenarios: (a) Solution 1, (b) Solution 2, (c) Solution 3 and (d) Solution 4.

3.1 Simplified model

A simplified model of an unreinforced masonry (URM) wall, composed of clay bricks and lime mortar (masonry compressive strength f_c=3.45 MPa; masonry shear strength/cohesion f_{v0d}=0.20MPa; shear stress τ_0 =0.09 MPa; modulus of elasticity E =1600 MPa; modulus of rigidity G =500 MPa), was developed in SAP2000 (CSI, 2025). The wall was represented using two-dimensional shell elements and accounted for two primary failure mechanisms: in-plane rocking and diagonal shear (Fig. 4).

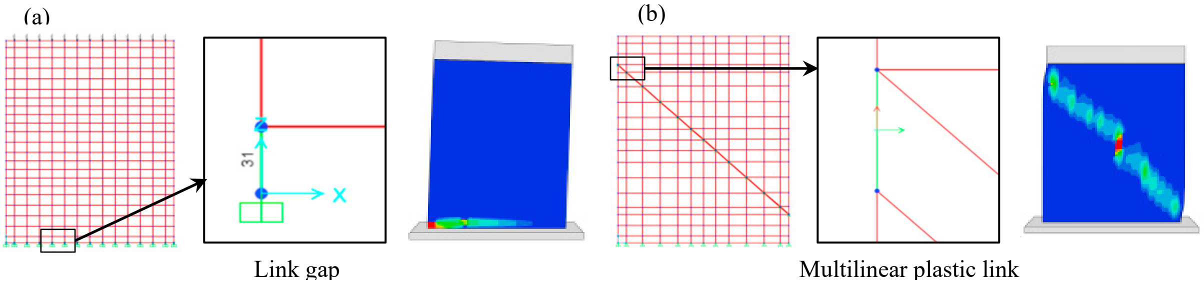


Fig. 4. Modelling details: (a) rocking model; (b) shear model.

Rocking behavior was simulated through nonlinear gap link elements placed at the wall base (Fig.4 Fig. 4.a), enabling uplift and rotation while preventing interpenetration with the foundation. Diagonal shear failure was represented by a 45° crack originating at mid-height, where multi-linear plastic links were introduced (Fig.4.b) and calibrated based on shear capacities derived from the Italian standards (NTC 2018, Circolare 2019) and relevant literature (Morandi et al., 2018).

Timber reinforcement systems were modeled with orthotropic elastic frame elements and plastic hinges to capture elasto-fragile post-elastic behavior. Connections were divided into mechanical fasteners (modeled with nonlinear links calibrated on experimental data by Gavric et al. (2011), Riccadonna et al. (2019), Rizzi et al. (2021), Cassol et al. (2021), ETA 11/0190) and traditional joints, represented by links with shear resistance based on timber properties (EN 338:2016 and Eurocode 5 (2014)) and multilinear plasticity for compressive stress distribution. A CLT configuration with three-layer orthotropic shell elements was also analyzed for comparison. All models were subjected to a vertical load of 0.10 MPa and to incremental horizontal loads applied at the top for nonlinear-static (pushover) analysis.

3.2 Detailed model

A detailed model of the cross-lap timber joint was developed for two main reasons: a) it represents the critical element of the system, essential to ensure sufficient frame stiffness and the effectiveness of the timber-to-masonry reinforcement (as inadequate stiffness could hinder the yielding of the connection); b) it is the system component for which the least experimental and bibliographic information on its mechanical behavior are available.

The joint was modelled using Midas FEA NX with 3D solid elements and an anisotropic plastic material model based on Hill's criterion (a generalization of Von Mises's criterion). Mechanical properties were based on C24 solid timber (EN 338:2016). Properties parallel to the grain were assigned along the main axis of the elements, while modulus of elasticity and strength perpendicular to the grain were used for the two transverse directions.

Two 300 mm segments of post and beam were simulated, and in-plane rotational loading and axial loading was applied through contact analysis using a "general contact" formulation, considering both normal and tangential interactions with a wood-to-wood friction coefficient of 0.4. To account for the orthotropic nature of wood and its brittle failure modes (e.g., tension perpendicular to grain), nonlinear elastic interface elements were also implemented at the notch area, with tensile and shear strength limits along the grain direction (Fig. 5).

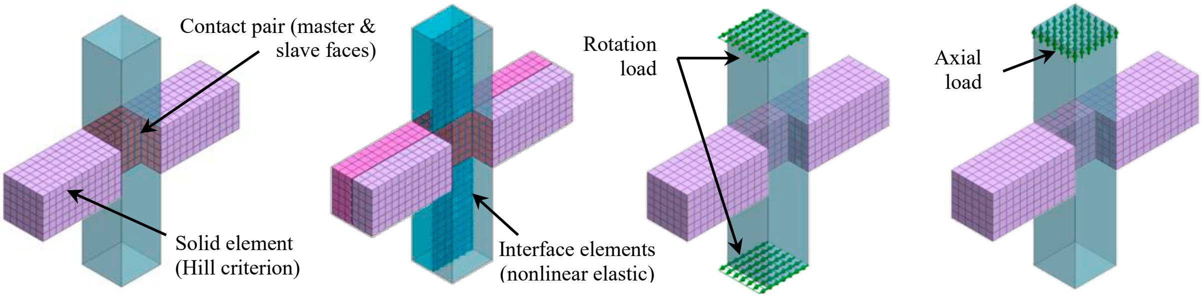


Fig. 5. Detailed numerical model main features and adopted loading conditions.

4. Analysis results

In this section, the results obtained from two numerical models are presented.

4.1 Simplified model

The simplified modelling approach enabled a comparative assessment of various timber-based reinforcement scenarios. Fig. 6 illustrates the force–displacement curves corresponding to both rocking and diagonal shear failure mechanisms. Overall, all reinforcement solutions significantly enhanced the performance of the unreinforced masonry (URM) wall, leading to increased strength and ultimate displacement capacity.

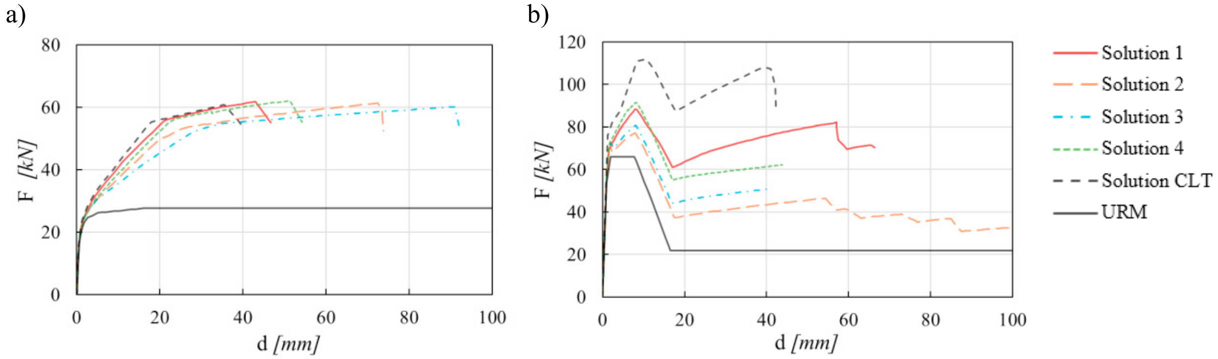


Fig. 6. Effectiveness of the different timber-based retrofit solution: (a) rocking behavior; (b) shear behavior.

In the rocking failure scenario, the retrofitted wall reached a peak load of ~60 kN, marking a 124% increase over the unreinforced configuration. As expected, hold-downs proved essential in sustaining loads after the base cracking.

Expectedly, pushover curve comparisons show that reinforcement type has little impact on initial elastic stiffness. However, the CLT panel delivered the best overall performance, followed by Solutions 1 and 4 the stiffest among the timber grid systems.

Under diagonal shear failure, performance differences between the reinforced walls were more evident. Increased stiffness correlated with higher shear capacity: Solutions 1 and 4 showed ~36% improvement, compared to the ~70% gain obtained with the even stiffer CLT overlay.

4.2 Detailed model

The results of the detailed cross-lap joint simulations are presented in Fig. 7. Among the various modeling strategies, the configuration assuming isotropic material properties (orange lines), with E_{90} and $f_{c,90}$ applied uniformly across all directions, combined with a high contact stiffness (Normal Stiffness Scale Factor = 1000; dashed lines), exhibits the most uniform stress distribution across the contact surfaces and the lowest deformation capacity. This response reflects a simplified but effective approximation of contact behavior under idealized loading conditions.

In contrast, the orthotropic material model (light blue lines; see also Fig. 8) captures a more realistic evolution of the internal force path. As loading increases, the resultant force becomes progressively inclined with respect to the grain direction, leading to increased stiffness and strength due to the directional nature of the material's mechanical properties. Finally, the most comprehensive model, incorporating potential brittle failure paths due to tension perpendicular to grain (blue lines), shows that only part of the joint's full "plastic" capacity can be mobilized before delamination failure initiates at the notch interfaces.

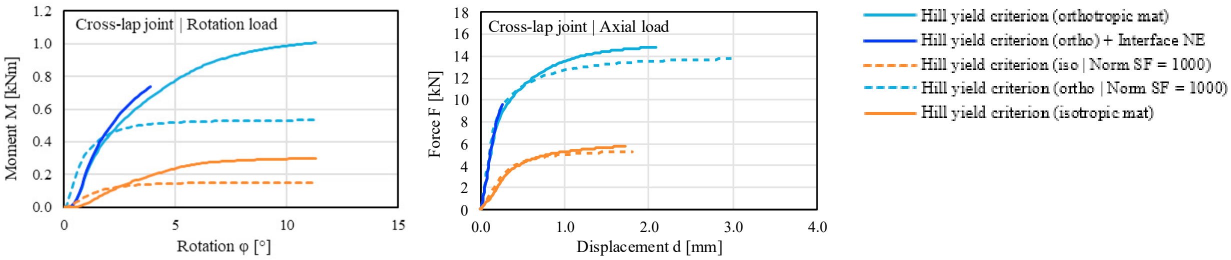


Fig. 7. Detailed numerical model outcomes in terms of M-φ and F-d curves.

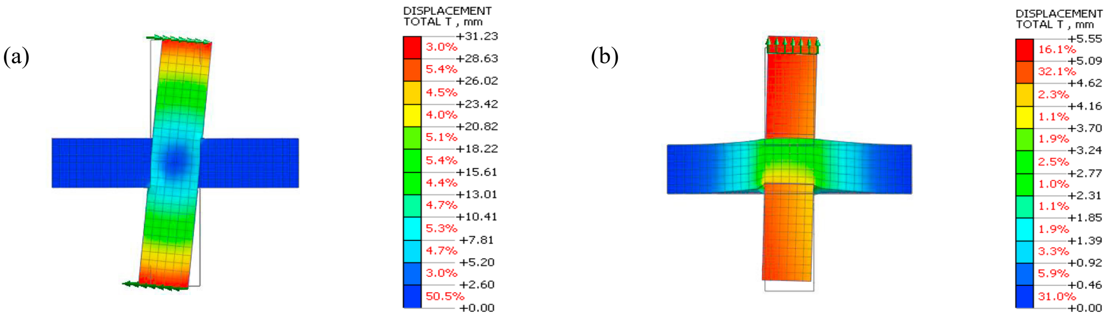


Fig. 8 Deformed shape and displacement contour plots for the detailed numerical model: (a) Rotation load (b) Axial load.

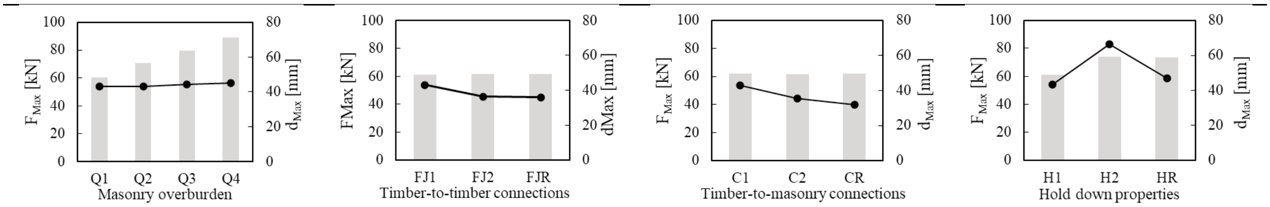
5. Sensitivity analysis

Among the most promising solutions for seismic performance (Solutions 1 and 4), Solution 1 was selected for further analysis due to its simpler construction (thanks to a less dense grid) and lower material demand.

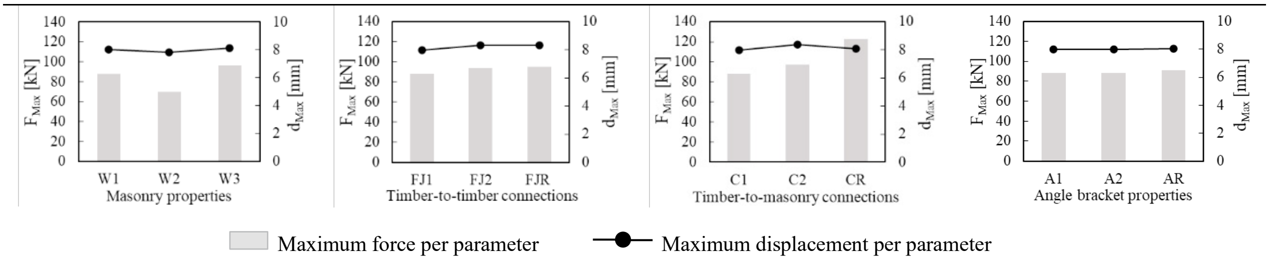
A parametric sensitivity study was conducted on this configuration, varying one parameter at a time to assess its effect on structural response, with each parameter linked to the most relevant failure mode (shear or rocking).

As shown in Fig. 9, increasing the vertical load notably enhances both capacity and displacement in the rocking mechanism, improving stability. Masonry type significantly affects shear strength, with regular, compact units offering higher resistance. Stiffer timber-to-timber and timber-to-masonry connections increase peak strength (F_{Max}) but reduce deformability (d_{Max}), revealing a trade-off between strength and ductility. Similarly, rigid base anchorage improves strength and stiffness but may limit seismic energy dissipation.

Rocking behavior



Shear behavior



Masonry overburden: Q1=0.10 MPa; Q2=0.15MPa; Q3=0.20 MPa; Q4=0.25 MPa.
Timber-to-timber connections: FJ1=screws and cross-lap joints; FJ2=only cross-lap joints; FJR=Rigid connections.
Timber-to-masonry connections: C1=dry connections; C2=adhesive connections; CR=Rigid connections.
Masonry properties: W1=Regular clay brick and lime mortar masonry; W2=Irregular tuff masonry; W3=square stone block masonry.
Hold-down properties: H1=Gavric et al. (2011) hold down properties; H2=Cassol et al. (2021) hold down properties; HR=rigid anchorage.
Angle-bracket properties: A1=Gavric et al. (2011) angle-bracket properties; A2=Cassol et al. (2021) angle-bracket properties; AR=rigid anchorage.

Fig. 9. Influence of parameters on the effectiveness of Solution 1.

6. Energy efficiency assessment of the integrated retrofit scheme

With the TimberGrid system, timber strengthening is combined with insulating layers to enable both seismic and energy retrofitting. To assess the system's energy performance, full-scale tests will be carried out in a climatic chamber at the *Sustainable Energy Laboratory of the University of Trento.* The testing process will be conducted in two successive phases: the first will evaluate the "as-built" condition (without finishes), while the second will examine the reinforced configuration, featuring the external application of the timber lattice system, covered with wood fiber insulation panels and finishing layers. The evaluation will employ a new method based on response factor theory (Danovska et al. (2024)). Unlike conventional steady-state procedures, these techniques enable the acquisition of reliable results while significantly reducing both the duration and energy consumption of the tests.

I Internal Side ① URM wall ② Breathable membrane ③ TimberGrid ④ Masonry-to-timber fasteners ⑤ Insulation panels
⑥ Waterproof membrane ⑦ Finishing E External Side

Fig. 10. Energy efficiency assessment: (a) insulating layers; (b) climatic chamber; (c) external side of wall specimen with breathable membrane and timber grid

7. Conclusion

The numerical investigation confirmed the effectiveness of a timber grid retrofit system connected to masonry through distributed point-to-point fasteners. Both simplified and detailed quasi-static models were employed to assess performance under varying retrofit configurations, masonry types, connection details, and vertical loads. Results showed substantial improvements in both in-plane strength and displacement capacity across all cases.

Solutions 1 and 4 were the most effective, with Solution 1 chosen for in-depth analysis due to its simpler assembly and lower material use. Detailed modeling of the cross-lap joint highlighted significant differences between modeling assumptions: isotropic configurations with high contact stiffness provided conservative but uniform responses, while orthotropic models captured enhanced strength and stiffness, along with the emergence of brittle failure modes such as delamination at the notch interfaces.

These results support the design of full-scale experimental tests on unreinforced, retrofitted, and repaired masonry walls using the proposed system. Further tests will focus on cross-lap joint performance, numerical model validation, and thermal chamber analysis to evaluate the system's thermal behavior.

Acknowledgements

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