multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

Codice progetto MUR: **PE00000005 – J73C22000520002**

Deliverable title: Report on development and validation of innovative techniques for integrated rehabilitation

Deliverable ID: DV 3.6.3

Due date: 15/03/2026

Submission date: 15/03/2026

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1 Technical references

Project Acronym	RETURN
Project Title	multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate
Project Coordinator	Domenico Calcaterra UNIVERSITA DEGLI STUDI DI NAPOLI FEDERICO II domcalca@unina.it
Project Duration	December 2022 – November 2025 (36 months)

Deliverable No.	DV 3.6.3 - Report on development and validation of innovative techniques for integrated rehabilitation
Dissemination level*	PU
Work Package	WP6 – Vulnerability of the built environment: assessment and reduction through sustainable solution
Task	T6.3 - Investigation of innovative methods and techniques for mitigation/adaptation
Lead beneficiary	UKE
Contributing beneficiary/ies	UNINA, ENEA, POLIMI, POLITO, UNIPA

* PU = Public

PP = Restricted to other programme participants (including the Ministry Services)

RE = Restricted to a group specified by the consortium (including the Ministry Services)

CO = Confidential, only for members of the consortium (including the Ministry Services)

1.1 Document history

Version	Date	Lead contributor	Description
0.1	10.03.2026	Giacomo Navarra (UKE)	First draft
0.2	12.03.2026	Valentina Lentini (UKE)	Critical review and proofreading
1.0	15.03.2026	Giacomo Navarra (UKE)	Final version

2 ABSTRACT

This document collects the contributions developed by various research units involved in the Return project. Specifically, the research topics covered by the deliverable are those falling within the VS3 spoke "Earthquakes and Volcanoes" and, more specifically, the Work Package 3.6, entitled "Vulnerability of the built environment: assessment and reduction through sustainable solutions." The research activities of this Work Package were then divided into several Tasks, and this document reports the research actions falling within Task 3.6.3 "Investigation of innovative methods and techniques for mitigation/adaptation".

The Task 3.6.3 explored innovative methods for seismic and volcanic risk assessment for management, mitigation and adaptation. It also considered methods for structural retrofitting that enable multi-risk mitigation and climate change adaptation.

The local research units which gave contribution to this document are summarized in the following, along with a brief description of their researches. ENEA research unit, coordinated by Anna Marzo, developed a study about the dynamic behaviour of a retrofit technique for masonry infills through an experimental campaign on shaking table. Also the energy performance of the proposed technique are taken into account. UKE research unit, coordinated by Giacomo Navarra and Valentina Lentini tackled the problem of the possible liquefaction of sand soils during earthquakes by setting up a novel 2D laminar box, provided with a pluviator for the preparation of the soil specimens, to be used in conjunction to the shaking table system available at L.E.D.A. The PoliTO research unit, coordinated by Paolo Castaldo, addressed the problem of the seismic retrofitting of bridges by means of friction pendulum devices, and structural rehabilitation of reinforced buildings by means of traditional/innovative reinforcement techniques also taking into account environmental criteria. The UniNA local research unit coordinated by Marco di Ludovico produced an investigation on the reduction of the vulnerability of masonry walls and infilled reinforced concrete frames with innovative materials and in a multis-risk environment. UniPA local research unit, coordinated by Lidia La Mendola and Piero Colajanni, gave a twofold contribution: a friction-based dissipative bracing device was analysed through numerical and experimental approaches and a technique was proposed to mitigate the seismic vulnerability of beam to column connection in reinforced concrete frames. Lastly, the local research unit of UniNA, coordinated by Beatrice Faggiano and Giulio Zuccaro, investigated about the use of timber-based exo-structures for the retrofit of existing structures by also taking into account the energy efficiency and the environmental impacts.

A significant amount of research and design recommendations were generated during the above-mentioned activities. This document, therefore, cannot contain all of them in detail due to length limitations. However, many of the results achieved have already been published or are in the process of being published in the most prestigious international journals in the field, thanks also to the financial support of the Return project.

This deliverable is organized as follows: section 3 contains the Table of contents as well as the list of Figures and Tables; section 4 contains the contributions from the local research units, whereas the section 5 is devoted to the Conclusions. Lastly, in section 6 a large selection of the referenced documents is reported.

3 Table of Contents

3.1 List of Tables

3.2 List of Figures

4 Contributions from local research units

4.1 Results of numerical and experimental tests of retrofit techniques for masonry infills combining structural and energy efficiency

This research activity was conducted by the local unity of ENEA, coordinated by Anna Marzo. To strengthen the resilience of the built environment, studying infill walls widespread in existing buildings is crucial as most of them were not designed for high thermal and mechanical performances. Dynamic experiments on such elements are rare and in most reported cases pseudo-dynamic tests are employed. This approach fails to realistically replicate the behaviour of panels, which require to be tested as part of the whole building to grasp 3D effects and interactions with the surrounding frame. Therefore, this activity concerns an extensive experimental campaign on a full-scale single-story reinforced concrete building with hollow brick infills, including surveys on structural and non-structural parts, carried out before and after soliciting it through Shaking Table. Once damaged, the specimen was strengthened with a lightweight, easy-to-apply, retrofit system and tested again. The approach intends investigate to what extent the seismic damage affects the dynamic response of the panels with and without reinforcement, meanwhile analysing through non-destructive tests energy performance of the envelope and integrity of the frame.

To deepen the behaviour of infill walls in dynamic states, a specimen has been built in the ENEA Seismic Hall and excited by Shaking Table. It is a full-scale single-story (3.5x3.5x3.5m) reinforced concrete frame, designed according to past Italian Code for non-seismic area, with infills having different thickness (Figure 1-a). When damage indicated incipient collapse of one of the walls, test on the as-built structure was stopped. Then, the specimen was repaired and retrofitted through a mitigation system, consisting of a fibre mesh applied by water-based adhesive (Figure 1-b, Figure 1-d) and re-exposed to seismic loading.

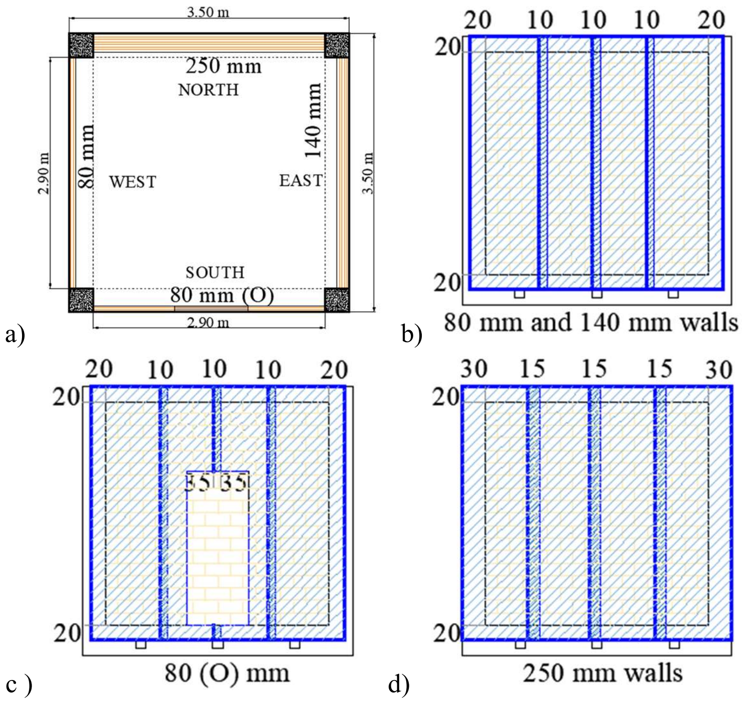


Figure 1: a) Specimen plan view. Retrofitting b) East and West sides c) South side d) North side.

The Shaking Table has the technical characteristics summarised in Table 1. The acquisition instruments consisted of 13 accelerometers channels, located on relevant points of frame and walls, and a 3D motion capture system with 13 near infrared cameras to track the displacements of 65 optical markers.

Table 1 – Technical characteristics of the ENEA Shaking Table.

SIZE	DOF	FREQUENCY	ACCELERATION	VELOCITY	DISPLACEMENT	MASS
4 x 4 [m]	6	0 – 50 [Hz]	3g peak	0.5 m/s	0.125 m	30 [t]

In Figure 2 the investigation plan is illustrated. It has been aimed at providing a comprehensive analysis of the specimen along the experimental campaign including repeated walls dynamic characterizations meanwhile checking the envelope energy performance and the structural elements integrity.

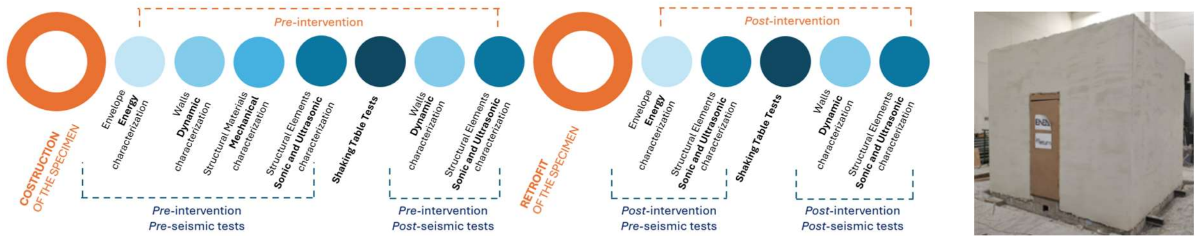


Figure 2: Investigation plan.

During tests, the specimen was subjected to a sequence of increasing seismic inputs interspersed by Random Tests (RT), that is white noise-based vibrations, to evaluate stepwise natural frequencies changes. In Figure 3a and 3b the Power Spectral Densities (PSDs) of the Out-of-Plan (OoP) acceleration signals at RT n.1 on East (red) West (green) and North (blue) walls, pre- and post- intervention respectively, are given. In Figure 3 the detail of trends of OoP frequency in the East wall is added. As it is evident, although reparation works combined with the mitigation system allowed only for a partial recovery of the initial stiffness, the curve of the retrofitted wall is stable, quite linear and with a final value higher than the unreinforced condition, despite a substantially higher peak of ground acceleration reached in the post-intervention tests ($1.6a_{g,ref}$ versus $1.3a_{g,ref}$). As additional result the intervention, designed to mitigate the walls vulnerability, did not worsen the energy performance as shown by thermal analyses which highlighted a transmittance slight reduction after repair and retrofit activities.

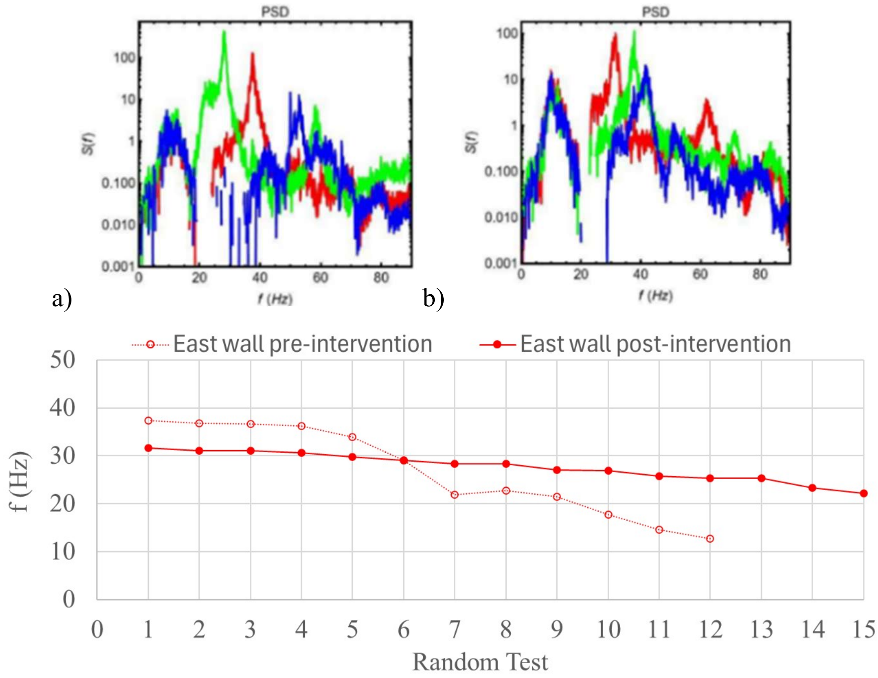


Figure 3: PSD at RT n.1 pre- (a) and post-intervention. (b) Trends of frequency in the East wall.

Moreover, along the phases of the experimental campaign the reinforced concrete frame was checked by Non-Destructive Tests (NDTs) determining the velocity of propagation of ultrasonic and sound waves through the structural elements. Being these velocities closely related to the stiffness of the material, NDTs were performed before and after the application of the seismic actions to assess their capability of detecting damage. It was found that after seismic loading, some columns retained their initial sonic velocities while others had a drastic reduction highlighting the presence of internal cracks. This behaviour, which will be object of further investigation, should be read in the light of the specimen mass and stiffness distributions also considering the presence of an eccentric mass located on the roof.

4.2 Shaking table tests and liquefaction behavior

The research outlined in this section has been carried out by the local research unit of UKE, coordinated by Giacomo Navarra and Valentina Lentini. A new laminar shear box was designed for shaking table tests at the Laboratory of Earthquake Engineering and Dynamic Analysis (L.E.D.A.) of the University of Enna "Kore" (Sicily, Italy) to investigate the liquefaction phenomenon and to validate advanced numerical models and/or the numerical approaches assessed to simulate and prevent related effects (Castelli et al. 2024a, 2024b, 2024c). The laminar box was designed for biaxial shaking on a 6-DOF large shaking table (Navarra et al. 2015). The box is rectangular in cross section and consists of 16 layers for a total height of 1600 mm. Each layer is composed of two frames with internal dimension of 2570 mm by 2310 mm for the inner frame and 2744 mm by 2770 mm for the outer frame. Each internal frame is supported independently by means of rods on a series of linear bearings connected to the external frame, while each external frame is supported independently by means of rods on a series of linear bearings connected to the surrounding rigid steel walls (Castelli et al. 2022).

The liquefiable soil deposit can be placed inside the laminar box using the raining method. It allows controlling the uniformity and the density of a large sand specimen (Bandini et al. 2019; Carvalho et al. 2010; Ueng et al. 2006). The saturated sand can be placed inside the laminar box also using the hydraulic fill deposition (Ecemis 2013; Thevanayagam et al. 2009). It involves the following steps: (1) the membrane is placed inside the box and filled with water to a precalculated depth; (2) soil and water mixture is pumped by a slurry pump into the laminar box; (3) at the same time, a water pump is used to return back the excess water from the laminar box. In order to perform shaking table tests, a pluviator was designed and built at L.E.D.A. (Figure 4) for preparing the soil specimen inside the laminar box by the raining method. The spreader consists of a hopper with external dimensions of 91.6 cm by 102.1 cm attached to a supporting frame; the hopper can move back and forth above the laminar box. The soil falls from a rectangular opening located at the bottom of the hopper.

a) b)

Figure 4: Pluviation system attached to a supporting frame above the laminar box at L.E.D.A.

Advanced tests to evaluate the liquefaction behavior of soils in laboratory involve cyclic triaxial (CTx) and cyclic direct simple shear (CDSS) tests (Lentini and Castelli 2019; Castelli et al. 2025). A laboratory testing programme, which included the execution of cyclic direct simple shear (CDSS) tests, was performed to derive the liquefaction resistance of a liquefiable sand to be used in shaking table tests at L.E.D.A. The maximum and minimum void ratio (e_{max} and e_{min}) were evaluated by the ASTM standard procedures. For estimating e_{max}, a standard mold (volume of 2830 cm^3) was filled by a standard pouring device (diameter of 13 mm) using the air pluviation technique. For evaluating e_{min}, the same mold was placed on a vertically vibrating table. The procedure also involves a base plate and an appropriate surcharge weight (total weight required of 25.6 ± 0.2 kg). The mold with the specimen was vibrated for 8 ± ¼ min at 60 ± 2 Hz.

The CDSS device is an advanced apparatus manufactured by Controls Group designed to allow a sample to be consolidated and then sheared under constant volume conditions simulating an undrained shear of a saturated specimen. The CDSS device at the Soil Dynamics and Geotechnical Engineering Laboratory of the University "Kore" of Enna is reported in Figure 5. The apparatus includes a control and data acquisition system with two 5 kN actuators that have internal displacement transducers. The standard sample is 70 mm diameter. It is positioned on a pedestal and restrained by a rubber membrane and a series of slip rings. The remoulding of the soil sample was carried out by the moist tamping.

Figure 5: CDSS apparatus at the Soil Dynamics and Geotechnical Engineering Laboratory.

Remoulded samples were consolidated under an effective vertical stress of 50 kPa. The cyclic shearing was applied using sine waves with amplitudes equal to the cyclic shear stress and a frequency of 0.5 Hz. The height of the samples was kept constant during the shearing process using the active height control. The liquefaction onset was determined based on the number of cycles required to reach a limiting single amplitude shear strain. Results of CDSS tests allowed defining the liquefaction resistance curves and provided useful information for the geotechnical characterisation of the liquefiable sand to be used in shaking table tests at L.E.D.A. (Castelli et al. 2024d; Lentini et al. 2024).

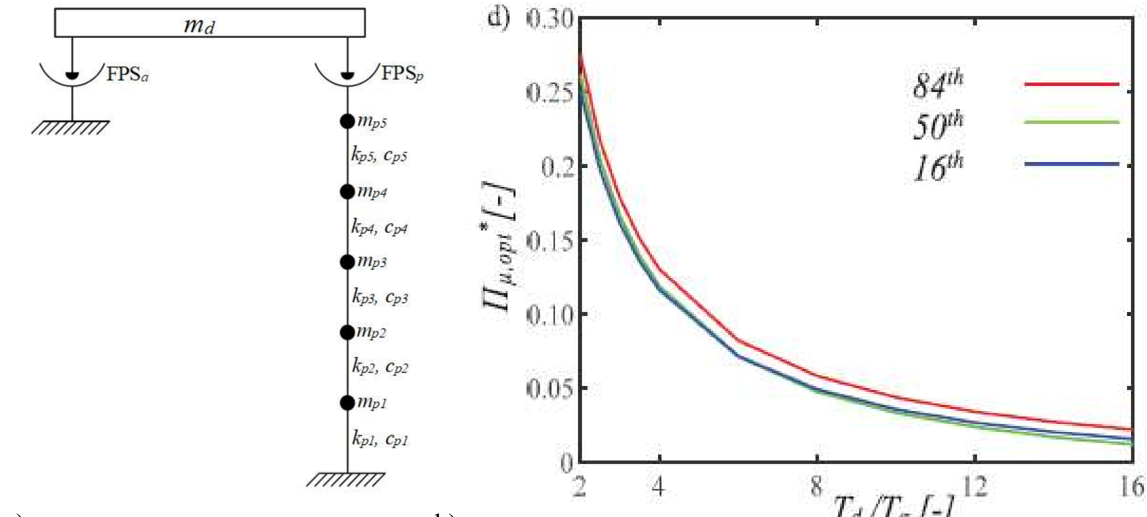
In order to characterize the new laminar shear box, shaking table tests were performed at L.E.D.A. The dynamic response of the system was widely monitored during the experimental tests. The test program consisted of white-noise excitation tests, sine-dwell excitations and simulations of the 1995 Kobe earthquake. The white-noise consisted of 4 random excitations having a very large frequency range (0.25 Hz-60 Hz) and root mean square accelerations equal to 0.5 m/s^2 and 2.0 m/s^2 for both x and y-directions. These tests were performed to investigate the natural frequency of the system. A sine-dwell test having a very large frequency range (0.5 Hz-60 Hz) and constant amplitude of 1 m/s^2 was carried out in x-direction. Finally, the 1995 Kobe earthquake was simulated considering different intensities of 25%, 50%, 75% and 100% of the input motion.

4.3 Seismic Isolation and Retrofitting

This research has been carried out by PoliTO research unit, coordinated by Paolo Castaldo. This research unit addressed the problems related to the seismic retrofitting of bridges/viaducts by means of friction pendulum devices (FPS), and structural rehabilitation of reinforced concrete/masonry buildings by means of traditional/innovative reinforcement techniques also taking into account environmental criteria.

4.3.1 Seismic Isolation of Bridges

As for the bridges, an analytical framework based on solving the equations of motion for the pile-abutment-deck system is employed. The dimensionlessness of the motion equations and the subsequent solution allow to determine the dimensionless response parameters with respect to the peak-ground-acceleration/peak-ground-velocity (PGA/PGV) ratio. The analysis is extended by investigating the response for different mechanical and dynamic characteristics of the system. The analysis framework provides the optimal design parameters for the isolator that minimizes response (Figure 6) as a function of the ratio between the isolated period and PGA/PGV. More details may be found in (Castaldo and Miceli, 2023).



a) b)

Figure 6: Viaduct model (a) and optimal FPS parameters (b).

4.3.2 Seismic Retrofitting of Buildings

As for the buildings, the definition of an optimization framework based on evolutionary algorithms (e.g., genetic algorithms) is envisaged, capable of determining the optimal position and sizing of the reinforcements, minimizing the environmental impact associated with the intervention (Figure 7). In particular, the framework provides for the minimization of an objective function that calculates the equivalent CO_2 emissions associated with each possible reinforcement configuration, determining among all those that meet the seismic demand, the one associated with the minimum value of CO_2 emissions. The framework also provides for the possibility of performing a comparison of economic convenience/environmental impact between alternative reinforcement strategies. More details may be found in (Sberna and Di Trapani, 2025).

Figure 7: Optimal retrofitting by reducing the environmental impact.

The following conclusions may be drawn: as for the bridges, the proposal led to define dimensionless optimal design parameters for the isolator able to minimize the dimensionless response of structural systems as a function of the ratio between the isolated period and PGA/PGV. As for the buildings, the definition of an optimization framework based on evolutionary algorithms (e.g., genetic algorithms) led to define the optimal position and sizing of the reinforcements, minimizing the environmental impact associated with the intervention. The framework also provides for the possibility of performing a comparison in terms of economic convenience/environmental impact between alternative reinforcement strategies.

4.4 Development and validation of innovative techniques for integrated rehabilitation

This research activity was conducted by the local unity of UniNA, coordinated by Marco Di Ludovico. The investigation aimed at reducing the fragility/vulnerability of masonry walls and infilled reinforced concrete frames with innovative materials in a multi-risk environment. In detail, the vulnerability against out-of-plane failure of masonry walls is assessed through the development of an analytical tool based on the yield line theory to derive fragility functions. Indeed, several hazards can induce out-of-plane failure of walls, among them earthquake, flood, tsunami and pyroclastic flows. Different interventions to enhance the out-of-plane capacity of walls are considered, with different levels of sustainability: organic composites, such as Fibre Reinforced Polymers (FRP), and inorganic composites, like Fibre Reinforced Cementitious Matrix (FRCM). The analytical tool, compliant with the CNR guidelines, has been validated over available experimental data on out-of-plane testing of masonry wallets (Del Zoppo et al. 2023). The multi-hazard fragility assessment of bare and strengthened masonry walls has been conducted in a probabilistic framework, accounting for aleatory uncertainties related to mechanical properties of materials. The resulting sets of fragility functions (see Figure 8) allow to assess the effectiveness of different interventions in vulnerability reduction of masonry walls for out-of-plane failure and will support the selection of the proper techniques for risk mitigation.

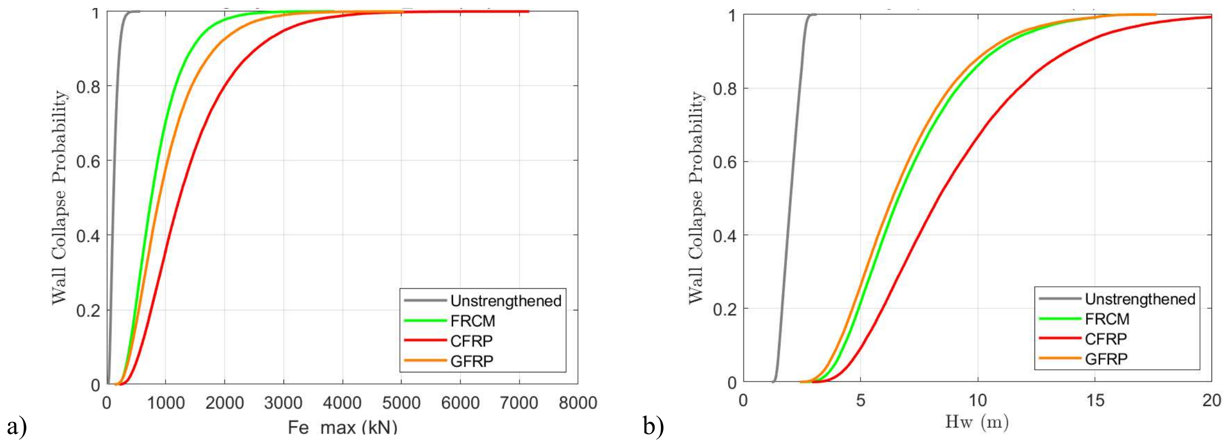
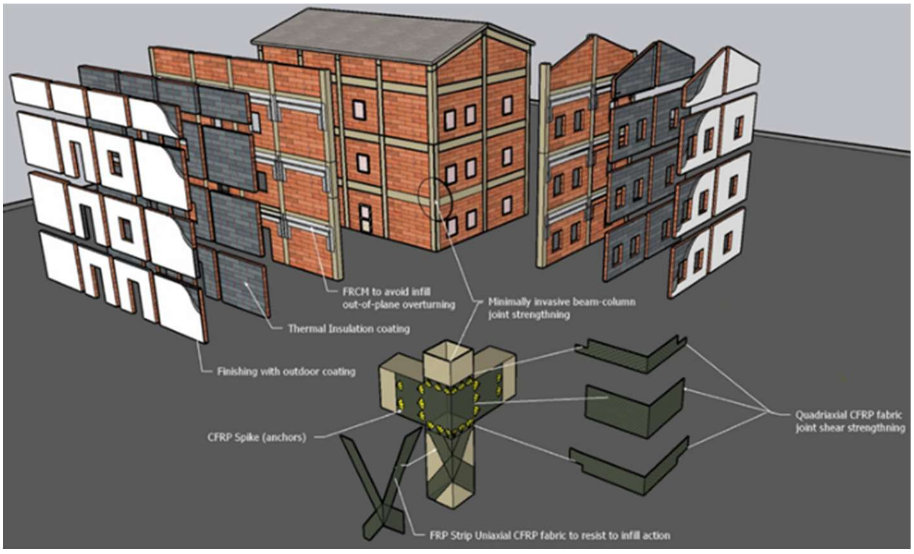


Figure 8. Fragility functions for hollow clay brick masonry walls for out-of-plane failure under seismic (a) and flood (b) loading conditions.

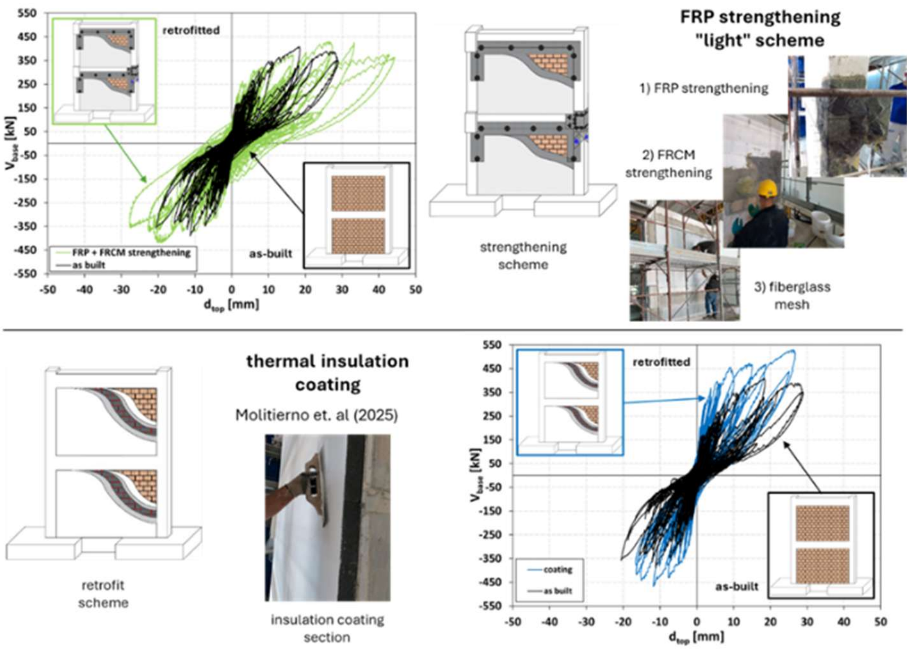
For reinforced concrete buildings, the work activities focused on the assessment and the validation of integrated retrofit solutions to improve the structural and the energy performance of existing reinforced concrete (RC) buildings. This is because the existing building stock were designed to withstand gravity loads only (GLD) or moderate seismic actions according to the regulations enforced in each country at that time, when the modern approaches to seismic design had not yet been introduced. In addition, these buildings were built before the introduction of modern energy standards. Thus, the energy consumption required to achieve acceptable comfort conditions for heating/cooling is still too relevant with respect to new buildings.

The proposed integrated strengthening solution is shown in Figure 9-a. It consists of FRP wrapping of perimetral unconfined beam-column joints (BCJs) to enhance their shear strength. To avoid the demolition of small portions of infill walls, FRP spike anchors are used instead of standard U-wrap at the end of beams and columns. FRCM/FRP strengthening are applied on exterior infills to enhance their in-plane and out-of-plane seismic capacity. The energy performance of the building is improved by installing a thermal insulation coating from the exterior of buildings.

The strengthening solution is experimentally validated on a full-scale multi-storey infilled RC concrete building, representative of a portion of an existing building under pseudo-dynamic (PSD) testing protocol (Molitierno et al 2025). For this purpose, a case study building designed in the period 1972-1981 to withstand moderate seismic actions was selected. The most severely damaged frame in the longest direction of the building was selected from the case study building and reproduced in full-scale in the laboratory environment. It consisted of a single-bay two-storey perimetral frame with a corner column. It was realized reproducing the geometry, mechanical properties and structural details of the real building.



a)



b)

Figure 9. (a) Details of the retrofit solution and installation phases for the proposed retrofitting; (b) Experimental results full-scale multi-storey infilled RC frame retrofitted with FRP+FRCM and thermal insulation coating

The first specimen was tested in its as-built configuration to characterize the seismic response under PsD loading protocol. The infill panels damaged during the tests were replaced to retrofit the specimen with the seismic and energy retrofit solutions as shown in Figure 9-b (top-right and bottom left side) and perform tests on these configurations.

The experimental results show that the seismic and energy interventions contribute to increase stiffness and strength of the structural system confirming the high effectiveness of the proposed solution to strongly increase the structural performances of the specimen (Figure 9-b).

In addition, the damage assessment demonstrates the importance of combining structural retrofits with energy retrofits interventions to reduce the vulnerability of the existing building stock towards moderate-to-severe earthquakes as well as the risk of wasting the investments made for energy efficiency improvements.

4.5 Innovative design procedures for retrofitting/strengthening interventions: friction-based dissipative bracing and beam to column connections for R.C. frame seismic vulnerability mitigation

The research summarized in this section has been performed by the research unit of UniPA and coordinated by Lidia La Mendola and Piero Colajanni. Hysteretic dampers are widely used for seismic retrofitting of r.c. frames due to their simplicity and reliability. Friction-based dissipative bracing, and beam to column friction connections for steel and r.c. frames are two of the most used devices. The design methods for hysteretic bracing were reviewed, highlighting the main limitations of the approaches currently available in the literature (Colajanni et al. 2024a); a full-scale prototype of a linear friction damper was subjected to cyclic testing, and in Ahmed et al. (2025) a design method for the distribution in plan and elevation of dissipative bracing for retrofit of r.c. frames was proposed; lastly, in Colajanni et al. (2026) the method is being perfected to optimize strengthening of r.c. frames with high irregularities in plan and elevation. In parallel, in Colajanni et al. (2024b) a review of friction dissipative beam to column connections for seismic design of MRFs has been conducted; the cyclic behaviour of an innovative friction device for RC column-Hybrid Steel Trussed Concrete Beam connection was scrutinized by FEM analysis and laboratory tests on a full-scale specimen (Colajanni et al. 2024c), and the design procedure and the effects of inclusion of such a device into a 2-storey RC frame are investigated by means of pushover analyses and non-linear time history analyses.

4.5.1 R.C. frame retrofitting by friction based dissipative bracing.

For seismic retrofitting of r.c. frames that as a whole have insufficient stiffness and resistance to horizontal actions, and reduced cyclic dissipative capacity, the use of braces equipped with dissipative devices is often chosen as a strengthening solution. Since the 1980s, dissipative brace design techniques have been proposed, exploiting the evolution of methods for predicting the seismic response of framed structures. Efficient design procedures have been established, addressing evaluation of the seismic behaviour and vulnerability of the existing structure, choice of the performances to be guaranteed, and design of the global stiffness and resistance of the braces. Less attention has been paid to optimized distribution of stiffness and strength across the elevation and plan, which is particularly critical for irregular configurations.

The pushover analysis has proven to be the most effective techniques for preliminary assessment of the overall weakness of the structure to be retrofitted and for determining the global stiffness and strength parameters of bracing systems. Target displacements are evaluated according to either the modified equal displacement rule, or an equivalent high-damped elastic SDOF system with secant stiffness at the performance point (Bruschi et al. 2022). Two predominant approaches exist for distribution of stiffness and strength in elevation: proportional distribution based on the structural properties of the system to be retrofitted (Mazza and Vulcano 2014), and strategic distribution aimed at correcting elevation and plan irregularities (Mazza and Vulcano 2015; Di Cesare and Ponzo 2017). Ferraioli and Lavino (2018) proposed a design method addressing some critical points that were not incorporated in the previous methods: dissipative brace–frame interaction, which produces an increment of the axial load in the columns with consequent decrease of the available ductility; effect of the modification of the modal shapes and the corresponding distribution of seismic forces along the height of the frame; and effects of the higher vibration modes in high-rise frames.

In Ahmed et al. (2025) a simplified method is proposed which enables the design of braces to mitigate vertical and plan irregularities in existing structures. The method is based on a modification of the first modal shape of the structure both in the elastic phase and after the sliding of the devices, aiming at a uniform distribution of the potential damage along the height of the structure, on an updated evaluation of the stiffness of the existing frame that takes into account the effect of the axial load induced by the braces, and limits variations of axial force in the columns so as to reduce losses in column displacement capacity; it also controls changes in the loads transferred to the foundations. To reduce the torsional effect due to plan irregularities, the stiffness and strength of dissipative bracing are distributed to obtain the coincidence of the center of stiffness and the centre of brace strengths and column reactions at the activation of the dissipative device with the centre of story seismic shear However, the numerical analyses showed that this resistance distribution can mitigate the torsional effects when the devices are activated, but not optimally during the sliding of the devices, during which the original irregular distributions of the column stiffnesses cause torsional effects. In Colajanni et al. (2026) the design method is refined using a most effective technique for the evaluation of the expected displacement, and controlling the torsional effects corresponding to both the displacements expected at the activation of the first devices and those at the performance point.

Moreover, an experimental campaign has been performed on linear dissipative devices with different types of friction materials, i.e. thermal-sprayed aluminium, and brass, to check their effectiveness. Finite element analyses using ABAQUS have been carried out to design the devices, check their functionality, and gain insight into the experimental results of the linear dissipative devices. The effectiveness of disc springs in limiting bolt preload variation in the device and the effect of the thicknesses of plates on the functionality of the linear friction dissipative device were deeply scrutinized. The results showed that thermal-sprayed aluminium, coupled with structural steel, is a good friction material as it provides stable hysteresis loops and a high friction coefficient compared to brass, and appropriately designed disc springs are able to limit bolt preload variation when the thickness of the plates of the devices is suitably designed.

4.5.2 R.C. frame seismic vulnerability mitigation by friction beam to column connection

The use of friction devices in the structural joints of RC buildings endowed with semi-prefabricated hybrid beams and traditional r.c. columns was proposed and investigated. The connection can prevent damage under seismic action—a key issue for this structural typology due to the reduced depth of the beam–column joint and the high reinforcement congestion typically present in that region. The efficiency of two different device schemes was initially investigated by FEM analyses, and the chosen solution use thermal-sprayed aluminium as friction material, and a central web steel plate and perfobond connectors, designed to ensure adequate stiffness and strength of the beam-to-friction-device connection. Cyclic tests on a full-scale specimen were performed, attaining a relative rotation of 60 mrad. The results showed that the beam-to-column joint provides fully stable hysteresis loops, no damage or cracking was observed, disc spring were. able to limit the loss of bolt preload. However, in some tests, due to the inclusion of new bolts, a sudden variation of bolt preload at the start of the cycles was detected, since friction surfaces and bolts need to adjust themselves at the beginning of the cyclic loading. Bolt preload remains constant in the subsequent cycles. It was also observed that the applied sliding force is not symmetric. This is due to two phenomena: an increase in contact pressure due to bulging of the plates, and variation of the lever arm of the external force due to large-displacement effects related to the test setup. Moreover, it was found that: - the loss of preload in the bolts due to long-term effects can be significantly reduced by maintaining the preload at a level between 30% and 60% of that permitted by the reference standard; - variation in the resultant of contact pressures between the friction angles and the central plate occurs when the steel angles are in tension or compression, due to deformation and bulging of the angles forming the friction plates.

Lastly, the effect of endowing a 2-storey RC frame with the tested dissipative beam-to-column connection (DBCCF), and supplementing it with a re-centering dissipative column-to-foundation connection obtained by endowing a friction connection similar to the tested one with threaded bars and disc springs, was evaluated by non-linear time history analyses. Comparison with the response of a frame with ordinary beam–column joints showed that in the latter the panel zone and first-storey column base section are the elements prone to the greatest damage, which in the presence of high-intensity earthquakes easily exceed the repairability threshold; in the DBCCF the beam end sections and panel zones experience negligible levels of damage. Nevertheless, the column bases still experience significant damage, and residual drifts higher than 0.5%. Re-centering dissipative column-to-foundation joint can avoid these drawbacks.

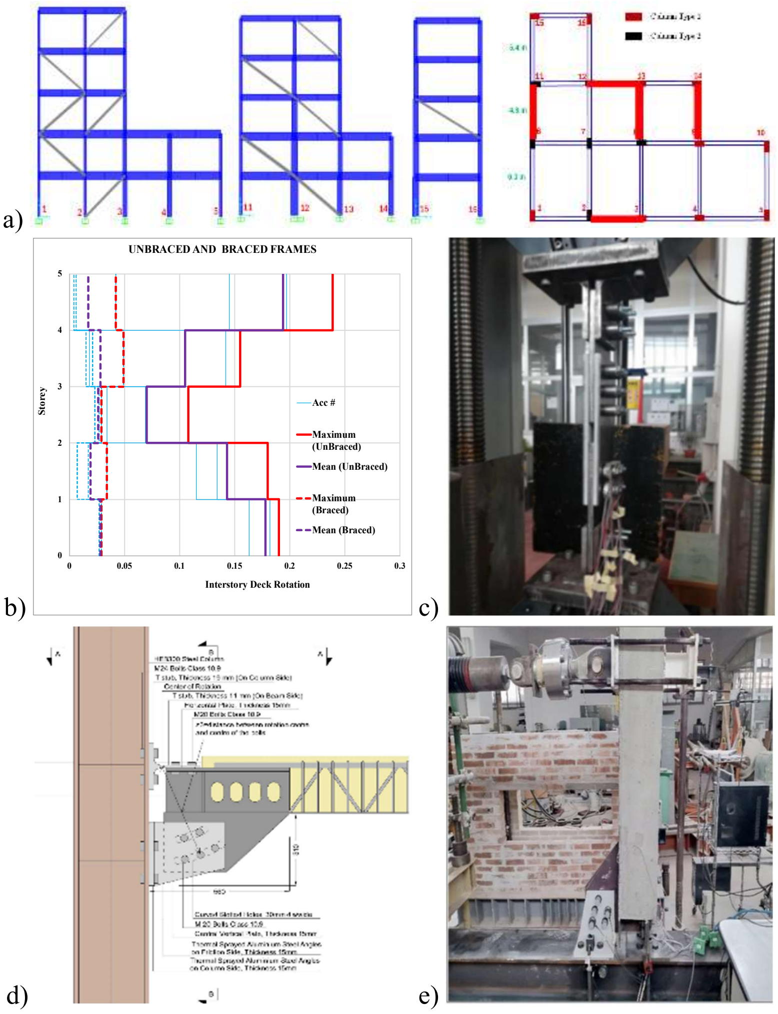


Figure 10: a) in plan and in elevation distribution of dissipative bracing; b) interstory deck rotation; c) linear dissipative device tested; d) design and e) tested specimen of beam to column dissipative connection.

4.5.3 Traditional and innovative composite materials for the reinforcement of masonry structures: shear strengthening of masonry panels

As part of the research activities dedicated to the use of both traditional and innovative composite materials for the reinforcement of masonry structures, a comprehensive study integrating experimental and numerical analyses has been carried out, with particular attention to the in-plane shear strength of masonry panels (Anzani et al. 2018, Del Zoppo et al. 2019). This parameter plays a crucial role in assessing the seismic behaviour and overall safety of existing masonry constructions. A distinctive feature of the research is the choice of a substrate representative of the historic built heritage of Sicily (Greco et al. 2020). The use of calcarenite, a material commonly found in traditional Sicilian masonry, allowed the investigation to reflect conditions closely aligned with those encountered in real structures. This choice strengthens the relevance of the results, which can therefore contribute to the development of effective strategies for the strengthening of existing buildings. To ensure a robust understanding of the material behaviour, an experimental characterization campaign was first carried out on the individual components of the masonry. The experimental campaign was based on diagonal compression tests performed on masonry panels, conceived to evaluate the effectiveness of Fabric-Reinforced Cementitious Matrix (FRCM) systems in enhancing shear capacity. Several types of reinforcing fabrics were considered, enabling a detailed comparison of their mechanical behaviour, while the role of mechanical connectors was also analysed to understand their influence on load transfer and the prevention of premature debonding (Di Leto et al. 2025, Di Leto et al. 2026). In addition to tests involving full FRCM systems, further experiments were conducted using only the reinforcing mortar without fibers. This approach made it possible to isolate and compare the mechanical contributions of the sole mortar layer, of the mortar combined with fiber reinforcement, and of the complete system consisting of mortar, fiber, and mechanical connectors. The comparison among these configurations contributed to clarifying the strengthening mechanisms and quantifying the effectiveness of each component.

Figure 11: Masonry panels geometry, FRCM applications and test set-up.

The experimental data were further interpreted through qualitative considerations derived from an extensive review of diagonal compression tests available in the scientific literature. The combination of original results and literature-based observations supported the development of insights that could form the basis for potential regulatory contributions. In particular, the study proposes indicative value ranges for the properties of composite materials and outlines correlations between mechanical parameters and expected structural responses. These correlations could prove especially useful when estimating bond and shear strengths in the absence of specific experimental tests. Moreover, the study includes recommendations on the use of mechanical connectors in low-quality masonry, highlighting their importance in preventing premature failures and ensuring the reliability of strengthening interventions.

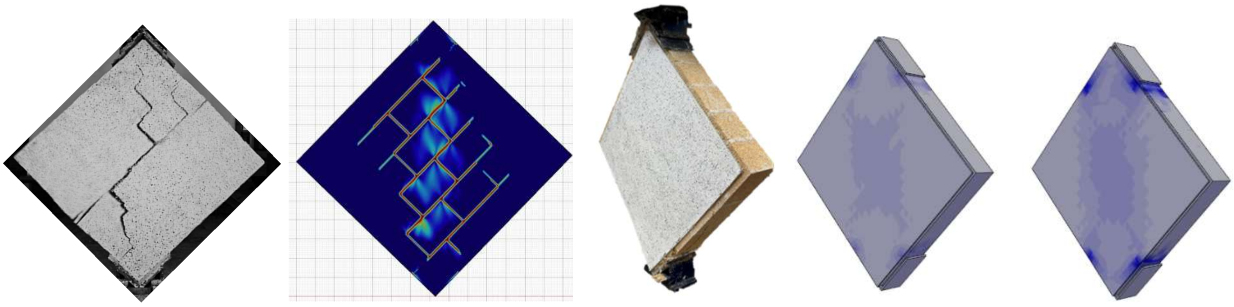


Figure 12: Masonry panels failure mode and numerical model.

4.6 Timber based systems for the seismic and energetic integrated retrofit of existing structures

This research activity, carried out by UniNA unit coordinated by Beatrice Faggiano and Giulio Zuccaro, gives a twofold contribution both to the development of timber-based systems for the retrofit of existing buildings and for promoting multi-hazard resilience. Owing to wood's intrinsic properties, such as lightness, high strength-to-weight ratio, sustainability, ease of construction and favorable energy performance, timber-based solutions represent an effective option for eco-friendly retrofit interventions. The proposed integrated approach addresses structural and seismic upgrading (resilience, life safety, service life extension, strengthening), architectural and urban improvement (architectural quality and environmental comfort) and energy efficiency (reduction of environmental impact and energy demand).

In particular, the research deals on one side with timber exo- and endo-skeleton systems for the retrofitting of existing buildings, on the other side with the mechanical characterization of a full-scale prefabricated timber-based physical prototype, specifically designed for temporary buildings in high-risk areas subjected to seismic, volcanic ashfall and thermal stresses. In particular, the mail goals of the overall research activity are listed hereafter: for skeletons, 1. to define timber-based retrofitting systems, 2. to identify the mechanical behavior of components and whole integrated systems, 3. to provide and validate the design rules for the timber based retrofitting systems; for the prototype, to assess the mechanical behavior of the full-scale timber-based physical prototype. At present the main products of the research activity are the definition and the mechanical characterization of the timber skeletons retrofitting systems, as well as the design of the preliminary experimental campaign for the mechanical characterization of the timber prototype.

4.6.1 Timber based systems for the seismic and energetic integrated retrofit of existing structures

Attention is given to exo- and endo-skeletons, for the seismic and energetic retrofitting of existing concrete and masonry constructions, by identifying the mechanical behavior of both individual components and whole systems, providing the design rules and validating the effectiveness through structural analyses (Faggiano and Iovane, 2016; Iovane and Faggiano, 2021). Horizontal actions can be transferred from the existing buildings by a bi-dimensional (2D) or a tri-dimensional (3D) timber system. As for the 2D-systems, they are placed in parallel or orthogonally to the masonry walls or RC frames. Concerning the 3D-systems, they can be distinguished as partial systems, located at selected part of the building, and spatial systems, wrapping all around the building (Iovane et al., 2022a; Figure 13). The systems can be realized with timber walls (CLT, LVL or light timber frames panels) or timber braced frames (X, V concentric braces and eccentric braces). The connection to existing buildings can be realized by links able to withstand forces due to earthquakes or to increase the dissipation capacity with on purpose additional devices.

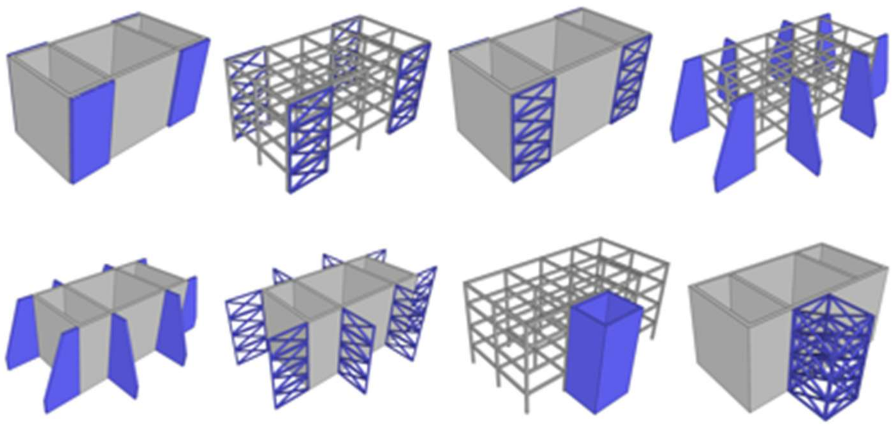


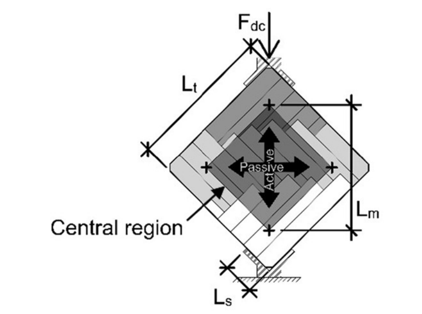
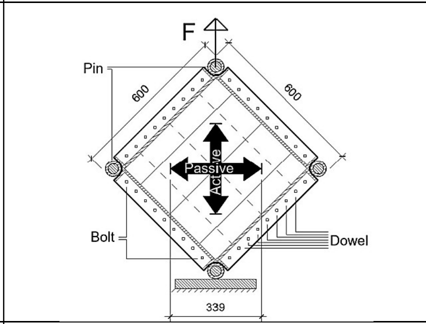
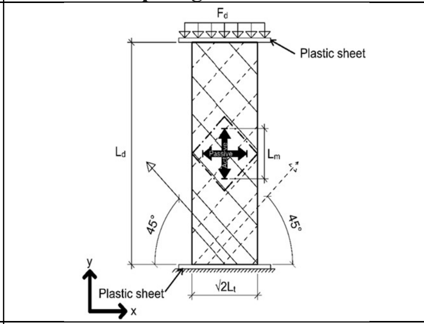
Figure 13: Timber-based exo- and endo-skeletons.

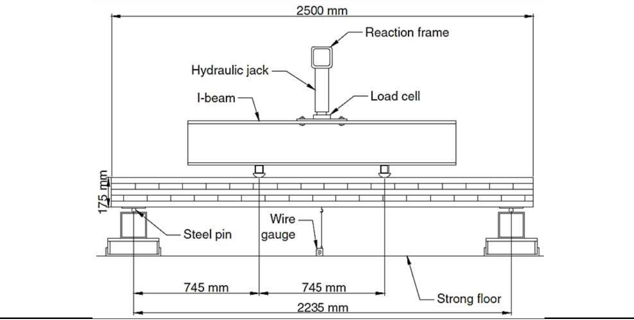
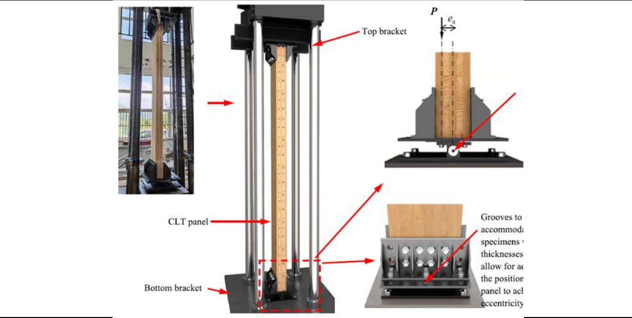
As for the use of Cross-Laminated Timber (CLT) walls, a comprehensive overview on the mechanical characterization of 2D CLT panels through experimental tests has been provided (Iovane et al., 2024a). It is worth noticing that for CLT panels, to determine strength and stiffness under shear load acting in-plane, three different experimental tests can be carried out (Figure 14): *diagonal compression test*; *picture frame shear test*; *diaphragm shear test*. In the diagonal compression test, shear modulus and strength are evaluated by applying a compressive load along one diagonal (active direction) until collapse, while the other diagonal (passive direction) is free to deform (Bjørnfot et al., 2017). In the picture frame shear test, compressive and tensile loads are simultaneously applied to the panel, each in a diagonal direction (Dujic et al., 2007; Turesson et al., 2019). The diaphragm shear test is the most recent test type, in which a vertical compressive force is applied on a rectangular CLT panel acting at an angle of 45° with respect to the grain direction, so that the main directions are inclined with respect to the panel edges. For CLT panels under out-of-plane actions, two different experimental tests can be carried out (Figure 14): *4-point bending test*; *compression-bending combination test*. The *4-point bending test* consists of two anvils placed in parallel, which can be fixed, translating or tilting supports, according to the test requirements; while in *compression-bending combination test* the panel is subjected to an eccentric compression (Shen et al., 2023; Figure 14). In order to study the cyclic behavior of the steel connections between the panels and between panels and structural elements of the frame systems, such as beams, columns, slab and foundation, three different types of tests can be performed: *tensile tests* and *shear tests*, to study the uniaxial (or mono-directional) behavior; *oblique tests*, to study biaxial (or bi-directional) behavior. The tensile and shear tests on connector devices consist of two CLT panels arranged orthogonally each other, in the case of a CLT wall-to-floor connection, or of a single CLT panel connected directly to the testing retaining frame, in the case of a CLT wall-to-framed structure connection. In the oblique test, the specimen parts are arranged obliquely each other and the connector devices are subjected to shear and tensile stresses. Angle brackets and/or hold-downs are used (Iovane et al., 2024a; Figure 14).

As for the use of dissipative timber framed structures as exo- and endo-skeletons, steel links, with a dissipation function based on cycles of plastic deformation, are studied as an alternative to traditional dissipative connections. At first simple structures, single-storey, single-span, are studied for assessing the main aspects of the global behavior. Therefore dissipative timber Moment Resisting Frames (MRF; Iovane and Faggiano, 2025) and Concentric Braced Frames with single diagonal (D-CBF; Iovane and Faggiano, 2026a) equipped with steel links are studied and compared to non-dissipative ones (Figure 15), by carrying out linear dynamic response spectrum analyses and incremental non-linear static analyses through SAP2000 (v.18) and Abaqus (v.18) softwares. Results have validated the proposed design criteria, based on the capacity design (Faggiano and Iovane, 2016; Iovane and Faggiano, 2021; Iovane et al., 2022b), according to which, dissipation occurs through the plastic deformation of the steel links, while the timber members and the connections remain in the elastic range with adequate overstrength as respect to the links, showing a small reduction of structural mass of dissipative structures as respect to the non-dissipative ones, up to about 13% and 6% for MRF and CBF structures respectively. The capabilities of hybrid timber-steel framed structures has also been evaluated through preliminary studies on single-storey, single-span structures with a Cross Laminated Timber (CLT) floor and dissipative timber-steel hybrid frames, such as Concentric Braced Frames with double (V- and X-CBF) and single diagonals (D-CBF) and Eccentric Braced Frames (EBF), characterized by timber/steel beams and columns with steel/timber braces. In particular, non-linear incremental static analyses were performed through the SAP2000 software to either assess the global seismic response, identify collapse hierarchies and determine the behavior factors.

Results have confirmed the efficiency and reliability of the proposed structural concept, highlighting the suitability for hybrid systems (Iovane et al, 2026a, b). At the same time, to assess local behavior, advanced numerical analyses on FE models were performed on the beam-to-column (Iovane and Faggiano, 2025) and link-to-diagonal joints (Iovane and Faggiano, 2026b) to evaluate the collapse hierarchy and the formation of the plastic hinge in the steel links, by using Abaqus (v.18; Figure 15). The mechanical behaviour of beam-to-column joints equipped with steel links (Figure 15) were investigated also through monotonic and cyclic experimental tests (Iovane et al, 2023; 2024b). The results of the numerical and experimental studies have validated both the efficiency of the system and the proposed design method.

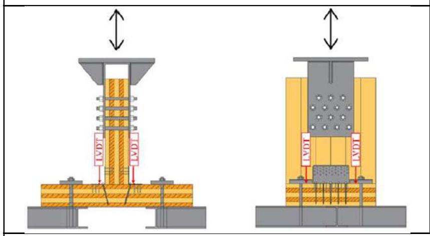
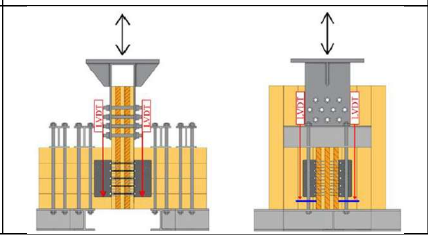
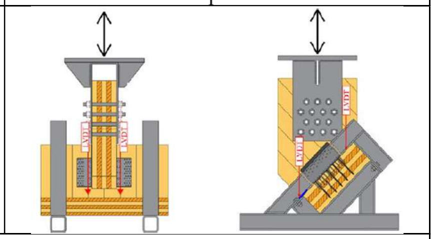
CLT tests

Diagonal compression test	Picture frame shear test	Diaphragm shear test
		
Sharif et al. 2021	Turesson et al. 2019	Sharif et al. 2021

4-point bending test	Compressive-bending test
	
Poulin et al. 2018	Shen et al. 2023

CLT Connection tests

Wall-to-floor connection

Tensile test	Shear test	Oblique test
		

D'Arenzo et al. 2018a,b

Wall-to-frame connection

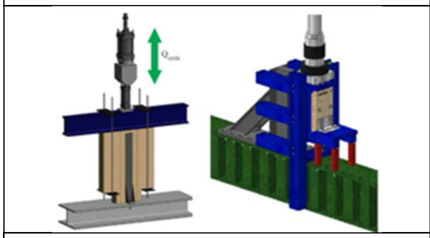
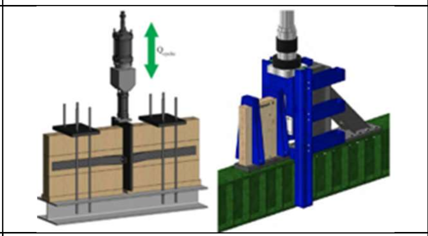
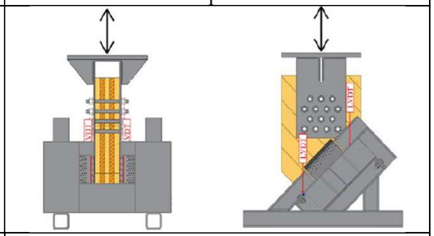
Tensile test	Shear test	Oblique test
		
Benedetti et al. 2019	Casagrande et al. 2016	D'Arenzo et al. 2018a,b

Figure 14: Test set-up on CLT walls and connections.

Also a procedure for the mechanical classification of timber beam-to-column joints, based on strength and stiffness, has been developed for filling the gap of current regulations and applied to more than 100 joint configurations, whose experimental characterization was available in the scientific literature (Iovane and Faggiano, 2026c). Results show that most of the joints can be classified as either pinned or semi-rigid.

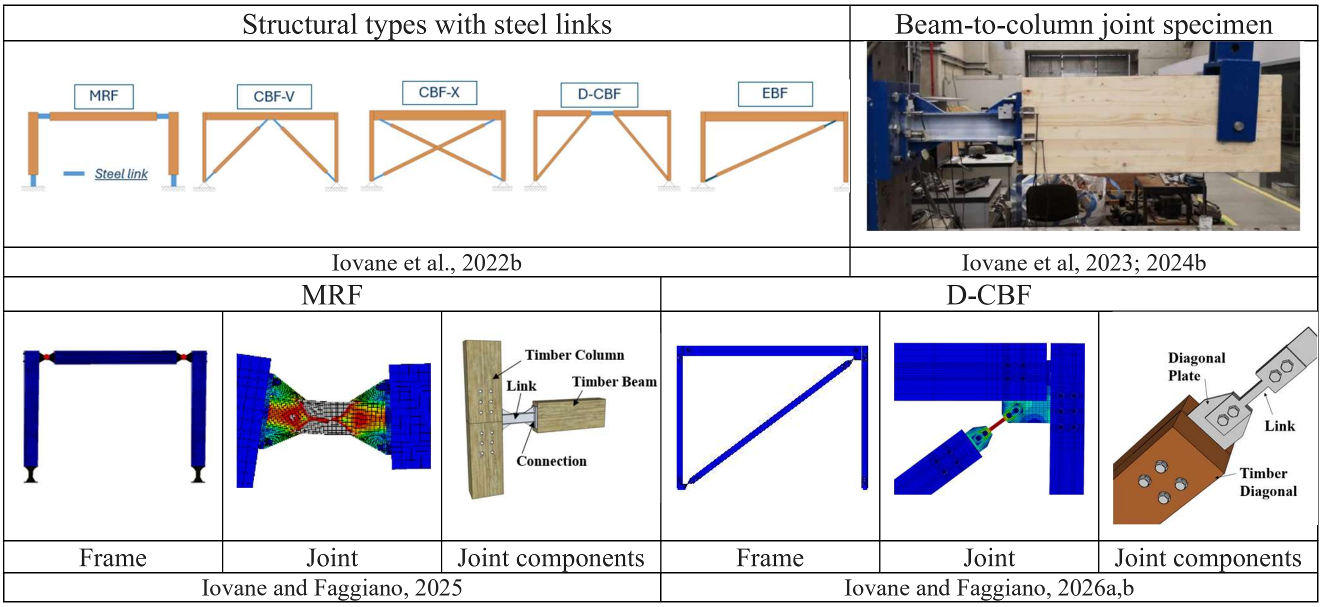


Figure 15: Seismic-resistant timber frame structures with dissipative steel links as exoskeletons for the retrofit of existing buildings.

The application of a 2D trussed perpendicular exo-skeleton system has been studied for the retrofitting of an existing r.c. structure. Specifically, a performance-based optimization framework for the design is implemented through a real-coded Genetic algorithm, for determining the optimal number and position of exoskeletons around the building. Both 2D steel and timber exoskeletons are designed and compared in terms of structural performance, economic cost and environmental impact. Results have shown that the timber exo-skeletons provide a satisfactorily enhancement of the building's performance, absorbing 50% to 80% of the seismic base shear. Both in terms of costs and Global Warming Potential, they excel in comparison with the steel alternatives, enabling a 30% cost reduction and producing approximately 30% lower emissions (Cucuzza et al., 2025; Figure 16).

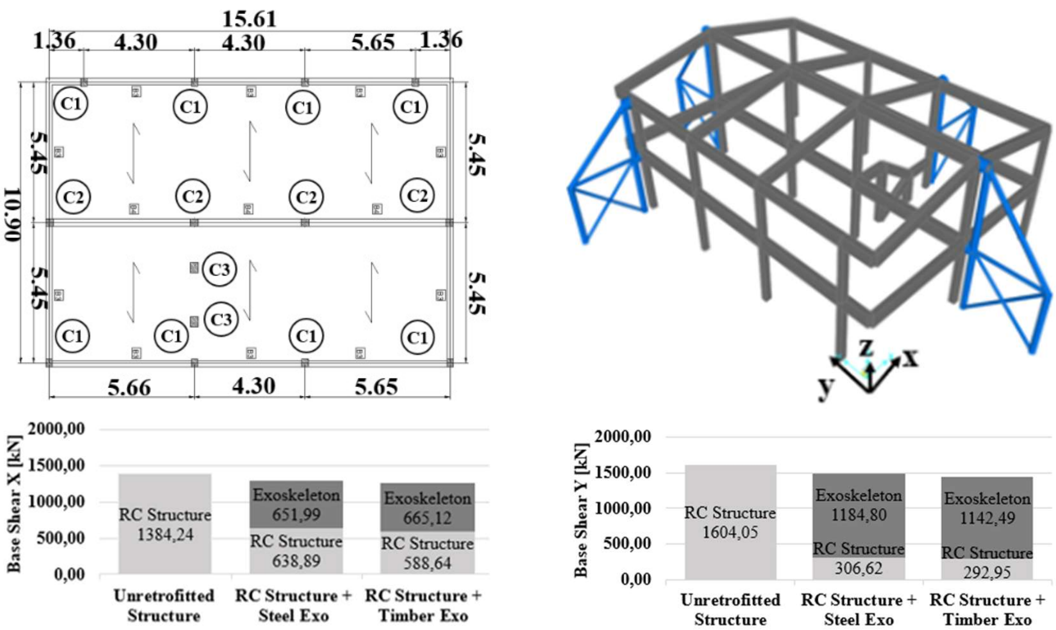
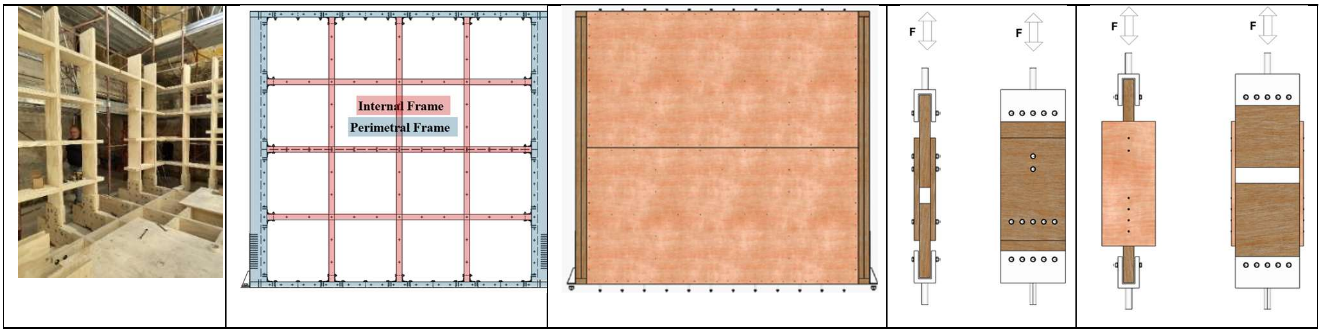


Figure 16: 2D trussed perpendicular exo-skeletons as retrofitting systems for an existing r.c. structure [m].

4.6.2 Mechanical characterization of the Prototype RETURN KIT through experimental tests

The full-scale physical prototype Return Kit (Figure 17) under study is a prefabricated system, featuring a waffle lattice structural configuration with half-lap dry-locking joints, made of phenolic plywood elements. It has been developed by Lancia D., Nocerino G., Leone M., Pone S. and Guadagno G.. The prototype has been erected by Brancaccio Costruzioni S.p.A. in the former Italsider area of Bagnoli, Naples. To this aim the structural verification under wind loads was carried out. Then, the mechanical characterization of components and structural system is required aiming at the validation for structural uses. Therefore at first the design of a preliminary experimental test program to evaluate the global and local behavior of the full-scale physical prototype, has been provided. It includes the following tests (Figure 17): (1) in-plane tests (2 monotonic and 1 cyclic tests) on the assembled system (walls); (2) connection tests (3 monotonic and 3 cyclic tests on frame-to-frame connection; 4 monotonic and 4 cyclic tests on frame-to-OSB panel connection).



Full-scale prototype	Wall	Connections

Figure 17: Full-scale physical prototype and test specimen.

In conclusion, timber exo- and endo-skeleton solutions emerge as suitable and efficient technology for achieving structural safety of existing buildings, thanks to timber's low self-weight, high strength-to-weight ratio and sustainability. A useful contribution of the research is the systematic overview of the experimental background on CLT panels and connections aimed at determining strength, stiffness, ductility and collapse modes. Regarding timber frames structures, the adoption of dissipative timber frames with steel links and the tailored capacity design principles are promising strategies, enabling controlled energy dissipation through the plastic deformation of the replaceable links, while preserving from damage timber members and connections. Moreover, the use of hybrid timber-steel structures maximizes the advantages of both materials, offering excellent results in terms of strength, stiffness and ductility of the study framed structural systems. It is worth noticing that comparative considerations indicate potential advantages of timber solutions over steel alternatives in terms of environmental impact and cost efficiency. The development of the Prototype RETURN KIT represents a further step toward practical implementation and validation at full-scale of timber-based systems for emergency management purposes. The designed preliminary testing program including monotonic and cyclic tests on both wall assemblies and connections, according to a multi-level experimental strategy, will allow to catch main aspects of the mechanical behavior of the components and the system, as a first step of the complete structural characterization of the prefabricated timber building. Future developments should focus on the standardization of experimental procedures, refinement and validation of numerical models, structural characterization by means of campaigns of experimental and numerical analyses on both components and global systems, definition of design criteria and constructional details, identification of range of application and performance targets also under cyclic and multi-hazard loading conditions, finally the transfer of outcomes into practical design and construction guidelines.

5. Conclusions

In the present deliverable document, the contributions developed by various research units involved in the VS3 spoke "Earthquakes and Volcanoes" spoke, Work Package 6 "Vulnerability of the built environment: assessment and reduction through sustainable solutions.", Task 3 "Investigation of innovative methods and techniques for mitigation/adaptation" of the RETURN (multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate) research project are collected.

A considerable body of research outputs and design-oriented insights was developed throughout the activities described throughout the document. The breadth and depth of these contributions exceed what can be comprehensively presented within the constraints of this deliverable, which therefore offers only a selective overview of the most representative findings. A substantial portion of the results has already been disseminated, or is currently undergoing peer review, in leading international journals in the relevant scientific domains. Hereinafter the most relevant conclusion of the researches are reported.

Regarding the research about a retrofit technique for masonry infill conducted by ENEA research unit, shaking Table tests have been performed to dynamically solicit a full-scale single-story reinforced concrete building with hollow brick infills. A sequence of seismic inputs, increased until the incipient collapse of the walls, was applied. Then, such non-structural elements were repaired and retrofitted through a fibre mesh mitigation system and seismically solicited again. Along the experimental campaign a comprehensive monitoring plan of the specimen health status was accomplished, including repeated walls dynamic characterizations meanwhile checking the envelope energy performance and the structural elements integrity through non-destructive tests. The effectiveness of the retrofit intervention was evaluated in terms of wall natural frequency trends and peak of ground accelerations reached in the pre- and post-intervention tests. Complementary outcomes in terms of thermal and thermo-hygrometric behaviour of the walls were checked without detecting any worsening after repair and retrofit activities.

The UKE research efforts were devoted to the design and realization of a 2D large laminar box to be used in conjunction with the shaking tables of L.E.D.A. to study the phenomenon of soil liquefaction in sand during earthquakes. In particular, a pluviation system has been provided in order to produce soil specimens. The PoliTO research unit addressed the problems related to the seismic retrofitting of bridges/viaducts by means of friction pendulum devices (FPS), and structural rehabilitation of reinforced concrete/masonry buildings by means of traditional/innovative reinforcement techniques also taking into account environmental criteria.

The UniNA research unit coordinated by Marco Di Ludovico developed a study about the reduction of the fragility and vulnerability of masonry walls and infills subjected to out-of-plane forces in a multi-hazard probabilistic framework. Moreover, the strengthening solution is experimentally validated on a full-scale multi-storey infilled RC concrete building, representative of a portion of an existing building under pseudo-dynamic testing protocol.

The UniPA research unit, coordinate by Lidia La Mendola and Piero Colajanni, proposed two different techniques to mitigate the seismic vulnerability of reinforced concrete frames. Specifically, a friction based dissipative brace and an innovative beam-to-column connection system have been studied by means of analytical and experimental approaches

Lastly, the UniNA research unit, coordinated by Beatrice Faggiano and Giulio Zuccaro, studied the possibility of using timber exo- and endo-skeleton solutions as suitable and efficient technology for achieving structural safety of existing buildings, thanks to timber’s low self-weight, high strength-to-weight ratio and sustainability,

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