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The Resume Project: Numerical Analyses and Laboratory Test

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Abstract. Europe faces significant challenges due to seismic activity, which frequently leads to extensive damage, particularly in seismically active regions such as Italy. Recent destructive earthquakes have underscored the urgent need for innovative strategies to improve the seismic resilience and energy efficiency of existing buildings. The RESUME project addresses these challenges by proposing an integrated approach to seismic and energy retrofitting. Its innovative methodology combines structural reinforcement with thermal insulation improvements, targeting reinforced concrete (RC) structures originally designed only for vertical loads.

A key feature of the project is the development of a “dry seismic coat,” composed of cork panels paired with a composite timber-aluminum alloy exoskeleton. This system enhances both the seismic and energy performance of retrofitted buildings by simultaneously improving strength, stiffness, and thermal insulation.

This article presents the implementation and preliminary results of shaking table tests conducted at the IZIIS Laboratory in Skopje. These tests involved infilled and retrofitted three-dimensional RC frames subjected to simulated seismic loads. The experimental program was designed to assess critical aspects such as: (1) the effectiveness of the retrofitting system in enhancing seismic safety, (2) the comparative energy performance of the system relative to conventional insulation methods, (3) the feasibility of a combined seismic-energy vulnerability assessment methodology for RC buildings.

Thus, the present paper details the design, setup, and execution of the tests, focusing on the experimental setup, specimen construction and instrumentation, and loading protocol development. Preliminary results are also presented highlighting the retrofitting system’s capacity to improve seismic behavior, while also indicating potential gains in energy efficiency, paving the way for further research outcomes.

Keywords: Aluminum alloy · Timber · Existing Building · Integrated Retrofit · Lightweight Exoskeleton

1 Introduction

The increasing awareness of seismic vulnerability and energy inefficiency in elderly buildings has placed urgent attention on the need for comprehensive retrofitting strategies, particularly in earthquake-prone regions. Many obsolete masonry and reinforced concrete structures, constructed before modern seismic standards were established, pose significant consequences in the event of an earthquake. As a result, ensuring structural safety while simultaneously improving energy performance has become a key priority in both research and policy discussions. Italy and several other European countries have witnessed the devastating effects of seismic events on outdated buildings, highlighting the need for innovative retrofitting solutions. In parallel, the growing emphasis on sustainability, coupled with rising energy costs, has reinforced the necessity of integrating energy-efficient solutions with seismic strengthening measures. Studies have demonstrated that combined retrofitting approaches not only enhance a building's resilience and thermal performance but also offer greater economic feasibility compared to isolated interventions [1].

To address these challenges, various retrofitting methods have been explored, incorporating both seismic strengthening and energy-efficient materials. Hybrid approaches include the use of fiber-reinforced mortars alongside insulation layers [2] or laminated timber paneling that not only improves structural integrity but also contributes to aesthetic enhancement [3]. Among the many available techniques, a widely adopted solution involves applying external reinforcements to building facades, combined with thermal insulation panels. Over the years, different configurations of this system have been developed, including cast-in-place reinforced concrete walls [4], timber-cement composite panels with integrated seismic resistance and timber-fiber insulation properties [5], as well as cold-formed steel frames with diagonal cross-bracing for enhanced lateral stability [6].

This study aims to advance the field of combined seismic and energy retrofitting by evaluating the performance of an innovative exoskeleton system composed of laminated timber and aluminum bracings or panels. The research follows a structured methodology, beginning with numerical simulations to determine the most effective reinforcement configuration. The optimal solution, whether bracing elements or panels, will then be experimentally validated through shaking table tests conducted at the IZIIS Laboratory in Skopje.

The experimental phase involves two identical 1:3 scale reinforced concrete structures with the same geometric and mechanical characteristics. One specimen which serve as a baseline without reinforcement, is already tested and the achieved results are herein presented. The second specimen will incorporate the optimized exoskeleton system based on numerical assessments. By comparing their seismic and energy performance, this research aims to provide insights into the feasibility, effectiveness, and practical implementation of this integrated retrofitting solution for existing RC structures.

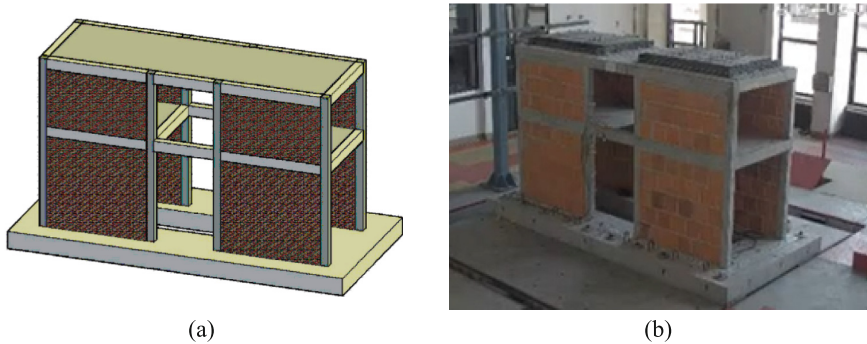


Fig. 2. Unreinforced RC structure: three-dimensional drawing (a) and real tested specimen (b).

2.2 RC Structure Reinforced with the Dry Seismic Coat

The numerical analysis focuses on evaluating two distinct external exoskeleton solutions, both incorporating aluminum alloy and laminated timber as primary structural materials. These systems are designed to enhance the seismic resistance of existing structures while simultaneously improving energy efficiency. Both configurations share a common structural framework, consisting of timber frames connected using galvanized steel plates and screws. The exoskeleton is anchored to the original structure via steel pins positioned at the beam-column joints, ensuring a strong yet adaptable connection.

The two solutions investigated differ in the design of their seismic-resistant elements, which are made of aluminum alloy components:

- X-Bracing Configuration – This solution employs concentric X-shaped aluminum braces.
- Shear Panel Configuration – Instead of bracing, this version integrates thin aluminum panels acting as shear walls.

The exoskeletons are installed on all exterior faces of the structure, except for the central span along the longitudinal direction, which remains open for inspection and monitoring during laboratory testing.

The aluminum elements are secured to the timber frame using galvanized steel angles, and they include connectors for attaching insulation panels. These insulation panels are made of recycled cork, offering both environmental sustainability and thermal efficiency. The aluminum components, including the diagonal braces and shear panels, have a uniform thickness of 2 mm and are composed of AW6060 aluminum alloy. Meanwhile, the timber frames are constructed from GI28 h laminated timber.

Further construction details, including the exoskeleton assembly scheme and the two configurations, are illustrated in Fig. 3, highlighting the integration between the reinforcement system and the existing RC frame.

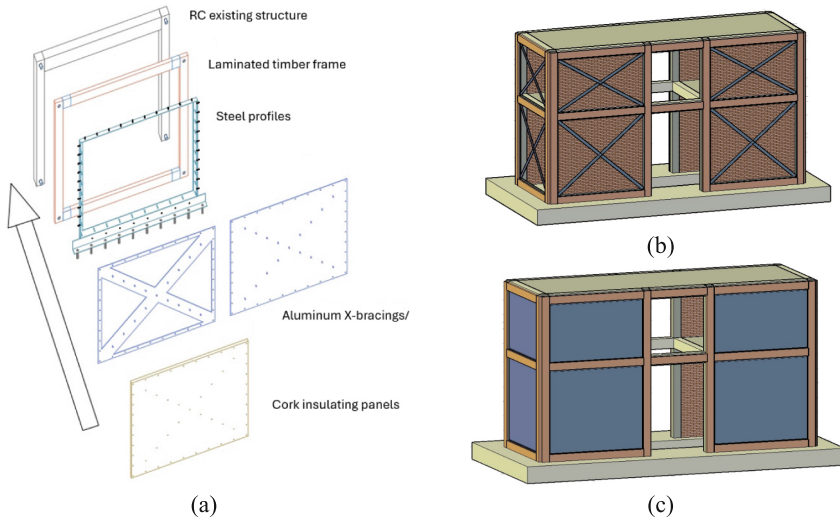


Fig. 3. Reinforced RC structure: exoskeleton assembly scheme (a), X-bracings configuration (b) and shear panel configuration (c).

3 Numerical Models

The 1:3 scale reinforced concrete (RC) structure was modeled using ProSap v.22, a structural analysis software developed by 2SI (Ferrara, Italy). To evaluate the effects of retrofitting, a modal analysis was conducted to identify the structure's vibration modes before and after reinforcement, followed by nonlinear static (pushover) analyses to determine the most efficient exoskeleton configuration for laboratory testing. In the pushover simulations, the infill walls were represented as equivalent struts, in accordance with established modeling techniques [7]. The seismic hazard level was assigned based on a location in L'Aquila, Abruzzo, Italy, with a topographic category of T1 and a soil classification of A, consistent with the Italian seismic code [8].

The first model was developed to reproduce the current state of the building, namely the unreinforced RC structure with infill walls (Fig. 4a). For the numerical representation of the exoskeleton solutions, two distinct reinforcement approaches were implemented:

- X-Bracing Configuration (Fig. 4b) – The actual diagonal braces were explicitly modeled in the structural analysis.
- Shear Panel Configuration (Fig. 4c) – The aluminum panels were simulated using ten equivalent diagonal elements, with their thickness matching that of the aluminum panel and widths determined using the strip model method [9].

The modal analysis of the three structural configurations (current state, X-bracing, and aluminum panel) revealed no significant qualitative changes in vibration mode sequences. The first vibration mode remained translational in the transverse (Y) direction, the second was torsional, and the third was translational in the longitudinal (X) direction. However, the reinforcement system significantly reduced the structure's natural period in its fundamental vibration modes, indicating increased stiffness (Fig. 5).

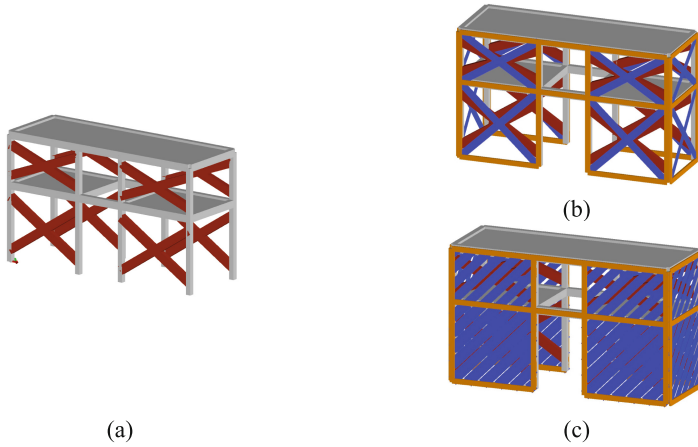


Fig. 4. Numerical models: current state (a), X-bracings configuration (b) and shear panel configuration (c).

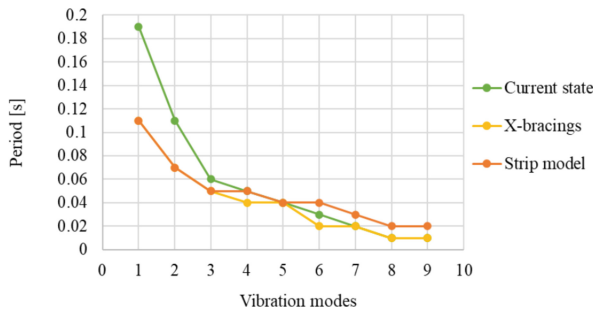


Fig. 5. Modal analysis: vibration periods mode 1.

Additionally, a reduction in maximum displacements and inter-story drift was observed, with the aluminum panel solution (strip model) exhibiting the most pronounced improvements (Fig. 6).

The results of the pushover analysis in terms of capacity curves of the structure, both before and after reinforcement, are presented in Fig. 7. The outcome shows notable increases in strength and stiffness due to the application of the dry seismic coat. The most significant stiffness and strength gains were observed in the transverse Y direction, where no infill walls were present. Moreover, the aluminum panel solution (strip model) demonstrated superior structural performance compared to the X-bracing system, achieving a greater increase in strength and lateral stiffness.

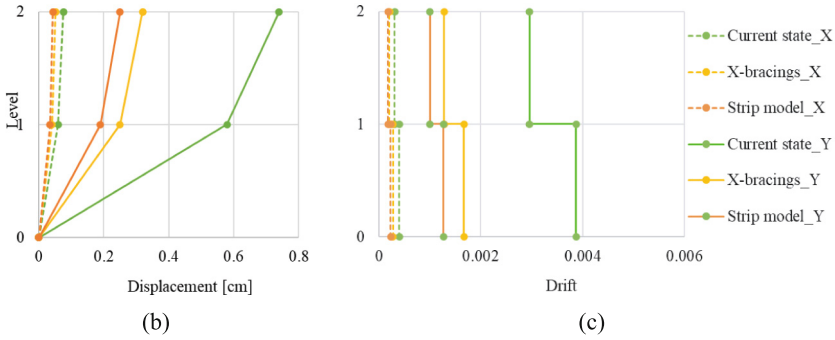


Fig. 6. Modal analysis: maximum displacements (b) and inter-story drift (c).

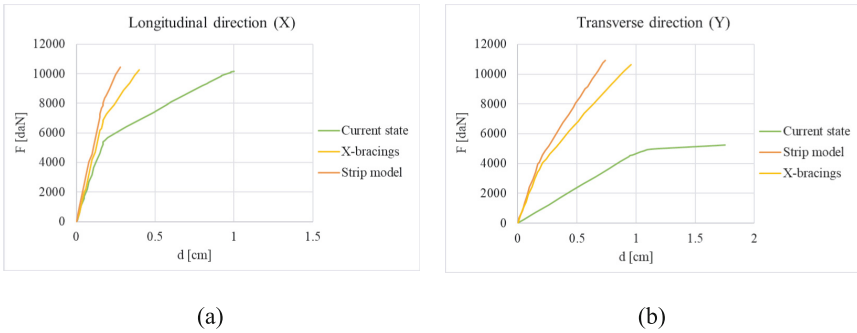


Fig. 7. Capacity curves of the pushover analysis: longitudinal direction (a) and transverse direction (b).

4 Selection of the Optimal Configuration

Overall, the implementation of the retrofitting strategies led to substantial improvements, as evidenced by both the modal and pushover analyses. The most pronounced impact of the exoskeleton was observed in the transverse (Y) direction, where the absence of infilled walls initially resulted in lower lateral stiffness.

However, clear benefits were also recorded in the longitudinal (X) direction, where infill walls were located at the end spans, further contributing to the system’s overall effectiveness.

The quantitative assessment of these improvements is provided in Table 1, which summarizes the percentage variations in dynamic properties relative to the original, unreinforced structure. Additionally, Table 2 presents the percentage increases in strength and stiffness for both exoskeleton configurations relative to the original structure, as obtained from the pushover analysis.

Table 1. Modal analysis: percentage variation of dynamic properties compared to the unreinforced structure.

| Configuration | Period | Max displacement | | Drift | |
|---------------|--------|------------------|--------|--------|--------|
| | | X | Y | X | Y |
| Brace | -42.1% | -31.6% | -56.8% | -32.1% | -56.8% |
| Strip | -42.1% | -42.1% | -66.2% | -42.0% | -66.2% |

Table 2. Pushover analysis: percentage variation of strength and stiffness compared to the unreinforced structure.

| Configuration | Max Force | | Stiffness | |
|---------------|-----------|--------|-----------|--------|
| | X | Y | X | Y |
| Brace | + 1.1% | + 103% | + 28% | + 344% |
| Strip | + 3.6% | + 108% | + 60% | + 377% |

These findings confirm that both retrofitting strategies significantly enhance the structural stiffness and stability of existing RC buildings. However, the aluminum panel configuration consistently demonstrated superior performance compared to the X-bracing system. Due to its greater effectiveness, the aluminum panel solution was selected for application on the RC specimen to be tested on the shaking table, ensuring the best performance in the experimental phase.

5 Experimental Test

As part of the experimental investigation, two models have been constructed: Model X and Model Y, both with identical geometric and mechanical characteristics. The testing is structured into three phases to analyze the effectiveness of the exoskeleton system as a seismic strengthening method.

- Phase 1: Model Y is subjected to increasing seismic loads until the expected deformations and damage levels are reached.
- Phase 2: An exoskeleton system is installed on the already damaged Model Y to evaluate its ability to enhance the seismic performance of the structure.
- Phase 3: Model X is tested with the exoskeleton system applied before the experimental testing, allowing for a direct comparison between a model strengthened prior to loading and one reinforced after sustaining damage.

At this stage, only Phase 1 has been completed. The following section presents the activities carried out during this phase.

The shake table used for dynamic testing at IZIIS measures 5.0 m by 5.0 m and has five degrees of freedom. It is supported by two lateral and four vertical MTS hydraulic pistons, controlled by an MTS Digital Controller 469D. The instrumentation of the tested models included accelerometers (ACC) - PCB Piezotronics, linear potentiometers (LP) – Microepsilon WDS, linear variable differential transformers (LVDT) – MacroSensors DC750, and strain gauges (SG) – KYOWA KFG, measuring accelerations, total and relative displacements, and strains, respectively. The data acquisition was performed using the National Instruments PXI modular system.

Specifically, 12 accelerometers were installed at different heights in two horizontal directions. Additionally, four linear potentiometers were placed at the slab level. A total of 10 LVDTs were used, of which two were positioned between the model and the shake table, while eight were placed around the column-beam connection. Furthermore, 30 strain gauges were installed, 24 of which were installed on the reinforcement bars in the columns at different heights, and six were attached to the concrete of the columns.

The testing program began with low-intensity white noise shake table tests to determine the dynamic characteristics of the system. Subsequent tests involved ground motion excitations with amplitudes scaled to progressively increasing intensity levels. The considered seismic inputs for the first model included the Adana 1998 earthquake (Mw 6.3), the Umbria 2016 earthquake (Mw 6.2), and a synthetically generated earthquake based on the Eurocode 8 spectra for Soil C. Figure 8 presents the time history of the maximum intensity seismic input applied during Phase 1. A full list of all tests performed on Model Y during Phase 1 is provided in Table 3.

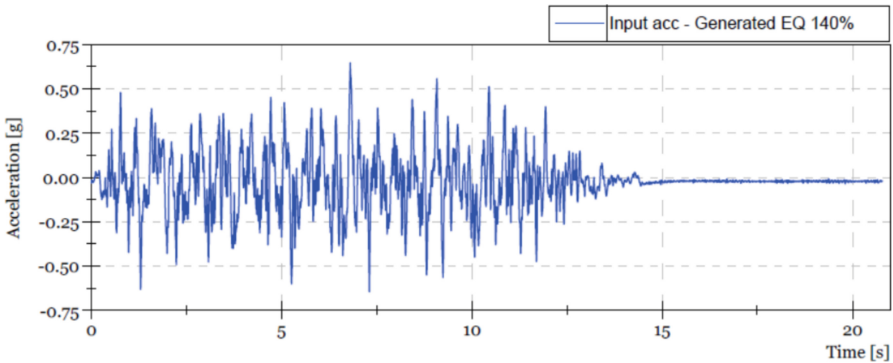


Fig. 8. Model Y – Phase 1. Input acceleration time history.

Table 3. Simulated earthquakes on Model Y.

| Test No | Type of excitation | Characteristics of the excitation | Input acc.[g] |
|---------|--------------------|-----------------------------------|---------------|
| 1 | White noise | f = 1 – 45 Hz; t = 300s | 0.01 |
| 2 | White noise | f = 1 – 45 Hz; t = 300s | 0.02 |
| 3 | White noise | f = 1 – 45 Hz; t = 300s | 0.05 |
| 4 | EQ1: Adana | 15% | 0.1 |
| 5 | EQ2: Generated EQ | 18% | 0.1 |
| 6 | EQ3: Umbria | 10% | 0.1 |
| 7 | EQ2: Generated EQ | 27% | 0.15 |
| 8 | EQ2: Generated EQ | 50% | 0.3 |
| 9 | White noise | f = 1 – 45 Hz; t = 300s | 0.05 |
| 10 | EQ2: Generated EQ | 75% | 0.45 |
| 11 | White noise | f = 1 – 45 Hz; t = 300s | 0.05 |
| 12 | EQ2: Generated EQ | 100% | 0.6 |
| 13 | White noise | f = 1 – 45 Hz; t = 300s | 0.05 |
| 14 | EQ2: Generated EQ | 100% | 0.6 |
| 15 | White noise | f = 1 – 45 Hz; t = 300s | 0.05 |
| 16 | EQ2: Generated EQ | 120% | 0.72 |
| 17 | White noise | f = 1 – 45 Hz; t = 300s | 0.05 |
| 18 | EQ2: Generated EQ | 140% | 0.84 |
| 19 | White noise | f = 1 – 45 Hz; t = 300s | 0.02 |

After the last test, severe damage was observed on the bare frame, with visible cracks, and approximately 80% of the infill on the ground floor collapsed. The natural frequency of the model decreased by about 80% from the beginning to the end of the testing. Figure 9 illustrates the model before and after testing.

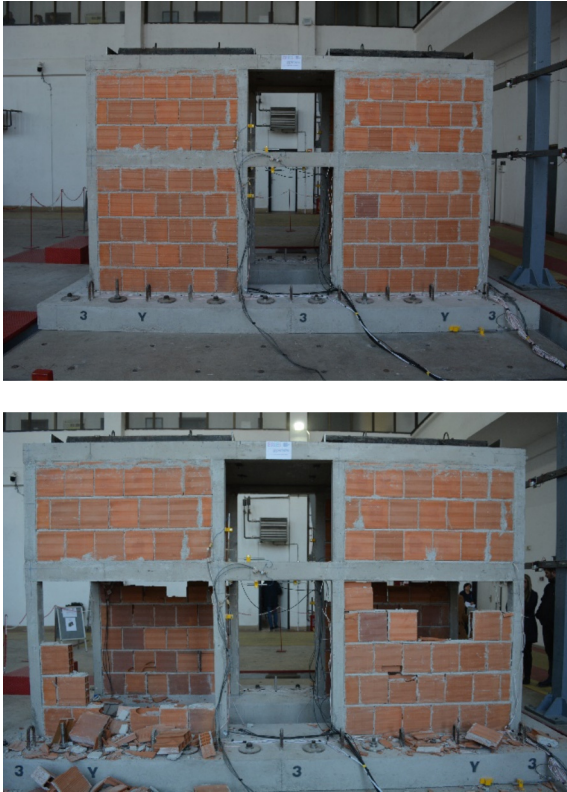


Fig. 9. Model Y – Phase 1, Before and After Testing

6 Conclusions

The research presented in this study underscores the significant potential of the RESUME project's integrated approach for seismic and energy retrofitting of existing RC structures. Through a combination of numerical modeling and experimental test, the effectiveness of the dry seismic coat system—composed of laminated timber and aluminum alloy elements paired with cork insulation panels—has been investigated. The numerical analyses, particularly the modal and pushover simulations, demonstrated that both proposed configurations—the X-bracing and aluminum shear panel systems—improved the dynamic and structural performance of a typical reinforced concrete frame designed without seismic criteria. Among these, the aluminum panel configuration outperformed the bracing system, yielding the most notable reductions in natural vibration periods, maximum displacements, and inter-story drifts. Quantitatively, this solution led to an over 40% decrease in dynamic response parameters and increases in lateral strength and stiffness exceeding 100% in transverse direction, with stiffness improving by as much as 377%, highlighting the critical role of the exoskeleton where infill walls were initially absent.

The experimental campaign involves the execution of shake table tests to validate the outcomes obtained through numerical simulations. In the first phase, testing was carried out on Model Y, which had no prior reinforcement. This specimen was subjected to progressively intensified seismic inputs until it sustained significant damage, including visible cracking and the near-total collapse of the ground floor infill walls. By the end of the testing phase, the structure's natural frequency had decreased by approximately 80%, indicating a dramatic loss of stiffness and structural integrity. These results clearly highlight the vulnerability of outdated reinforced concrete frames under seismic loading and emphasize the urgent need for effective retrofitting strategies. Future work will involve installing and testing the exoskeleton system on both intact and previously damaged structures, specifically Model X and Model Y, during Phase 2 of the experimental program.

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