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ADVANCING SEISMIC DESIGN AND ASSESSMENT THROUGH EXPERIMENTAL TESTING: INSIGHTS FROM THE ERIES PROJECT

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Abstract

Seismic design and assessment of structures hinge on accurately quantifying the non-linear behaviour of various structural and non-structural elements within the built environment. Experimental testing has become a cornerstone of earthquake engineering, providing invaluable insights into key structural behaviours that can be either designed for or mitigated against. This paper presents ongoing experimental activities at the Eucentre Foundation, under the auspices of the ERIES project, funded by the European Union. The project facilitates collaboration between research groups across Europe and leading research infrastructures as part of the transnational access and joint research initiative. The experimental facilities such as 9DLAB and MOBILAB at the Eucentre Foundation play a central role in these efforts, offering unparalleled flexibility, mobility, and adaptability in test setups—capabilities that are unique on a global scale. This study highlights several experimental research efforts, including the characterisation of the energy dissipation capacity of masonry infill walls and the exploration of sustainable retrofitting solutions for enhancing the capacity of rubble stone walls. Additionally, the paper discusses innovative in-situ testing of base-isolated buildings using a mobile shaking table. These advanced and adaptable experimental testing facilities not only deepen our understanding of the seismic behaviour of structures but also pave the way for new research directions in earthquake engineering. By harnessing these capabilities, researchers can better address the challenges of seismic resilience, leading to safer and more sustainable designs.

Keywords: experimental testing; structural performance; built environment; seismic performance.

1. Introduction

Natural disasters continue to inflict significant harm globally, impacting buildings and infrastructure, as well as causing profound economic and societal disruptions. Recent seismic events, such as those in L'Aquila (2009), Central Italy (2016-2017), Samos Island in the Aegean Sea (2020), Albania (2019), and Croatia (2020), have had considerable societal effects. For instance, the 2020 Aegean Sea earthquake resulted in an estimated €400 million in economic losses and left around 15,000 people homeless. In Albania, the November 2019 earthquake claimed 52 lives, injured 3,000 individuals, displaced 14,000 people, and destroyed more than 14,000 buildings. The Petrinja earthquake in Croatia also caused extensive damage, with additional challenges in reconstruction due to geotechnical issues, soil liquefaction, and the formation of sinkholes.

The ongoing impacts of these disasters underline the need for further research and technological innovations. Addressing this need, the ERIES project (European Research Infrastructures for European Synergies, www.eries.eu) responds to the European Commission's Horizon Europe call INFRA-2021-SERV-01-07. ERIES aims to provide transnational access (TA) to advanced research infrastructures in structural, seismic, wind, and geotechnical engineering, enabling ground-breaking research. This project offers access to leading experimental facilities, facilitating research that addresses hazard-related losses, risk management, and the development of innovative solutions for a greener, more sustainable society.

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This paper offers an overview of the experimental work at the Eucentre Foundation in Pavia, Italy, as part of ERIES. Researchers from Portugal, Turkey, the UK, and the Netherlands contribute to these activities, all aligned with ERIES' broader research goals. Each TA project is introduced, along with a summary of current achievements.

2. Developments at EUCENTRE Foundation testing facilities

To date, four Transnational Access (TA) projects (Table 1) have been completed at the EUCENTRE Foundation, utilising the advanced facilities of 9DLAB and MOBILAB. The following details summarise each project, including information on the user group leader, the institution, and the country of origin of each transnational access team. The subsections below offer an overview of each project, highlighting the experimental activities conducted at EUCENTRE Foundation to date.

Table 1. List of transnational access projects currently hosted at the Eucentre Foundation

Project Acronym	**Title**	**User Group Leader**	**Institution**
ERIES-RESTORING	REtrofitting of STOne masonRy using INnovative Grid-based composites	Rita Bento	Instituto Superior Técnico, University of Lisbon
ERIES-ENFRAG	ENhancing state-dependent FRAGility through experimentally validated Energy-Based Approaches	Roberto Gentile	University College London, United Kingdom
ERIES-SUPREME	Seismic oUt-of-Plane REsponse of Masonry gablEs	Francesco Messali	Technische Universiteit Delft, The Netherlands
ERIES-PASFIT	Long-Term Performance Assessment of Base Isolated Buildings through Field Testing	Haluk Sucuoglu	Middle East Technical University, Turkiye

2.1. ERIES-RESTORING

2.1.1. Overview of project

The seismic assessment/retrofit of existing masonry buildings has become in the past years a matter of high priority in seismically prone countries with a significant presence of built cultural heritage, such as several European and Mediterranean countries, accentuated by recent and mandatory legal sources. Moreover, the change of focus from building replacement to rehabilitation of the existing stock is a step towards greater sustainability, a topic for which more and more awareness is being raised.

The proposed project aims at spanning the information gap about factors affecting the seismic effectiveness of Composite Reinforced Mortars (CRM) applied to existing rubble stone masonry buildings by experimental research. The in-plane cyclic behaviour of innovative strengthening solutions compatible with historic masonry materials will be tested on full-size rubble stone masonry piers and will be compared with the non-retrofitted pier response. CRM, consisting of a glass-FRP mesh embedded in natural hydraulic mortar, will be applied to one or both sides of the specimen. Imposing double-fixed boundary conditions, two different aspect ratios will also be investigated. Moreover, the influence of the horizontal load rate will be studied by performing in-plane cyclic shear-compression tests with quasi-static and high-rate protocols.

The outcomes will provide useful data for the future development of design guidelines and building code requirements, currently missing, about the design of CRM as a strengthening solution for existing masonry structures. This will contribute to the reduction of their vulnerability and of the associated losses after earthquake events.

2.1.2. Experimental activities to date

The ERIES-RESTORING project has successfully completed its main phases. Key achievements include the design and construction of test specimens (see Figure 1) and setups, detailing the geometry and materials (masonry, mortar, CRM components, connectors), and adapting existing facility

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components. Essential structures, such as RC elements and test wallets for material characterisation, have been built. Comprehensive material tests have been conducted, covering CRM components, mortar, and masonry wallets under vertical and diagonal compression. Seven full-scale cyclic test piers were constructed and tested to evaluate their performance. Currently, the user group is analysing the data, interpreting results, and engaging in joint dissemination activities.

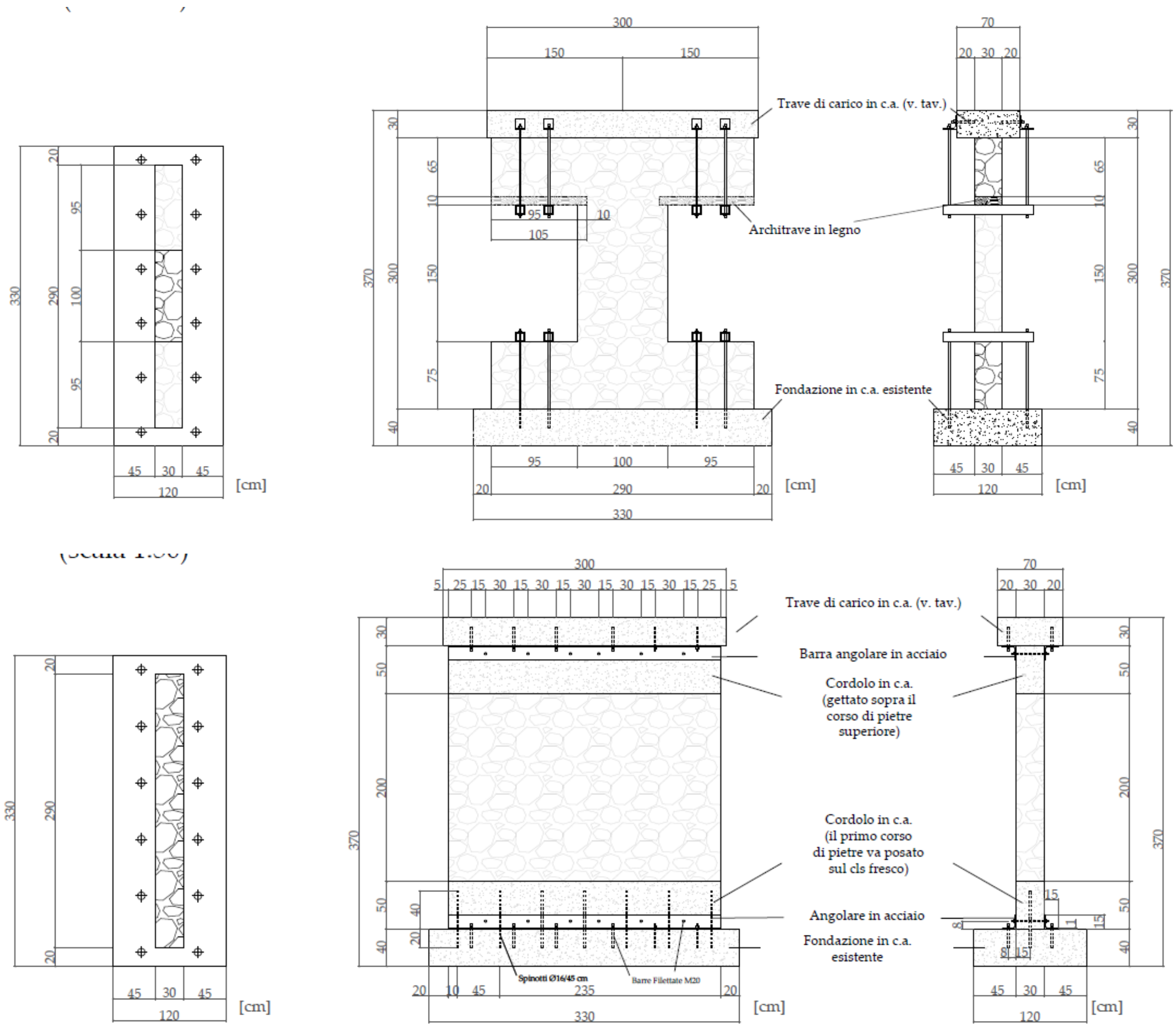

Figure 1. Specimen typologies and geometry for the ERIES-RESTORING project

2.2. ERIES-ENFRAG

2.2.1. Overview of project

ERIES-ENFRAG advances state-dependent earthquake fragility assessment methodologies. The project focuses on masonry infill walls experiencing cumulative states of damage due to combinations of in-plane (IP) and out-of-plane (OOP) actions, commonly quantified through two different peak-based engineering demand parameters (EDPs). ERIES-ENFRAG explores the experimental validation of hysteretic energy-based fragility assessment approaches, which are: 1) currently based only on analytical and/or numerical validations; 2) only considering one type of action/damage mechanism. ERIES-ENFRAG will pave the way for similar cumulative-damage tests for different structures/structural components while providing experimental data on the IP and OOP response of masonry infills. ERIES-ENFRAG aims at a robust consideration of damage-accumulation, particularly

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relevant in mainshock-aftershock conditions, and will also shed further light on the appropriateness of IP and OOP loading protocols used in experimental testing.

2.2.2. Experimental activities to date

The ERIES-ENFRAG project has completed all main phases, focusing on integrating numerical simulations with experimental efforts. Numerical models were improved and calibrated using EUCENTRE's existing test database on similar specimens. Construction included three main infill specimens, wallettes, and material samples for characterization tests, minimising uncertainties from environmental factors and labour variations. Comprehensive testing was performed (see Figure 2), covering IP and OOP mixed protocols, as well as wallettes and material samples. Data processing by EUCENTRE staff has delivered clean datasets for analysis. Currently, user groups are engaged in data analysis, interpretation of results, and collaborative dissemination activities.

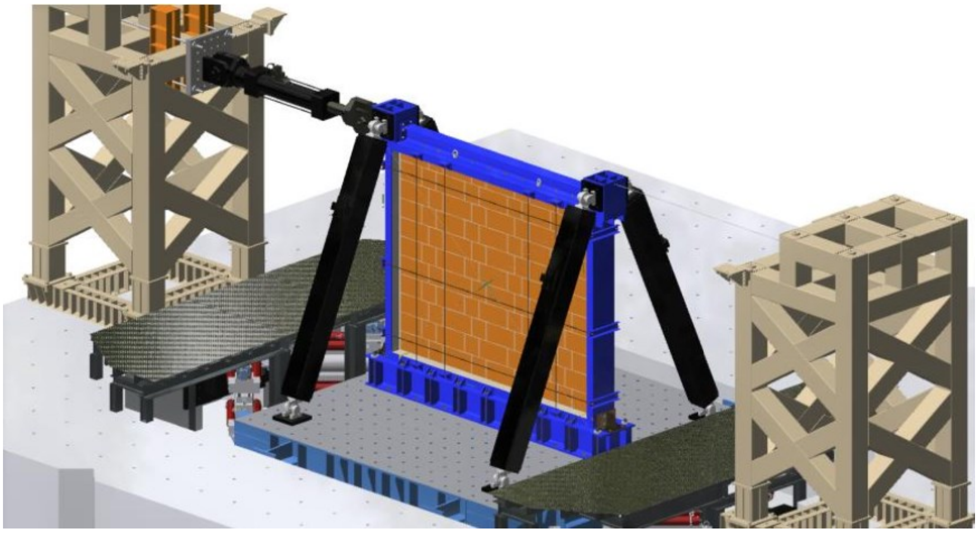

Figure 2. Test setup for the ERIES-ENFRAG project

2.3. ERIES-SUPREME

2.3.1. Overview of project

Typical low-rise existing masonry buildings in Europe commonly feature unreinforced masonry (URM) walls, complemented by diverse pitched roof configurations supported or finished by masonry gables. Such buildings also constitute a large part of the building stock for several seismic-prone countries, including both areas subject to natural hazard and induced seismicity. In such buildings, the masonry gables are often associated with the highest seismic vulnerability. The evidence of this seismic vulnerability has been widely documented in the aftermath of past earthquakes. This vulnerability can be attributed to multiple factors, including their high slenderness, poor connections to the roof structure, and their positioning at the uppermost part of the building, exposing them to amplified seismic excitation with respect to the ground motion while being subjected to low values of overburden load. Additionally, the interaction of the gables with flexible roof diaphragms can also contribute to the seismic vulnerability of the coupled system, due to the possible further amplification of the seismic motion through the timber elements. However, the amount of experimental data regarding the performance of URM gables is extremely limited, and it can be mostly inferred from tests that simulate a complete building and are not specifically focused on these structural elements.

The project here proposed aims therefore at improving the understanding of the seismic out-of-plane response of masonry gables within existing masonry buildings, a subject of fundamental interest to enhance the safety and seismic performance of existing masonry structures.

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The project will produce novel experimental data on the dynamic behaviour of URM gables, which is currently missing from published literature. The experiments will adopt idealised and easily numerically replicable boundary conditions, which can be simulated conveniently via numerical simulations. The tests will therefore be used as benchmarks to allow refinement and calibration of existing numerical modelling approaches, as well as the development of new tools based on single-degree of freedom systems. A blind-prediction contest open to international research groups will be set up to foster the calibration process. The generated experimental data and the calibrated numerical models will serve as basis for the improvement of available guidelines for the OOP seismic assessment of URM gables in existing masonry buildings. The results of the test results and of the prediction contest, as well as the recommendations to improve assessment guidelines will be published on a special issue of a peer-reviewed journal.

2.3.2. Experimental activities to date

The ERIES-SUPREME project has successfully completed all primary phases. Key milestones include the design and construction of the dynamic test setup (see Figure 3), incorporating steel elements and RC foundations, and the incremental dynamic testing of URM gables. Complementary material characterisation tests were performed at the University of Pavia to ensure representativeness. Numerical modelling was conducted to define dynamic seismic inputs, simulating interactions between gables and flexible or semi-rigid retrofitted roof diaphragms. Dynamic tests of three gable walls were performed using the EUCENTRE 9D System. Data processing, analysis, and interpretation of results are complete, while dissemination activities and the final test report are currently underway.

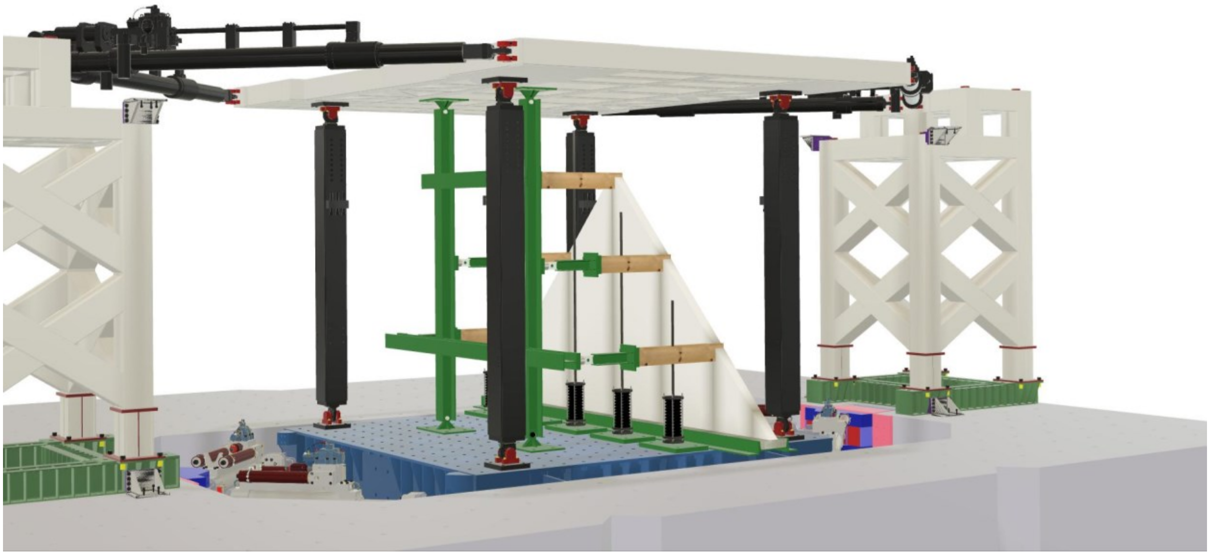

Figure 3. Test setup for the ERIES-SUPREME project

2.4. ERIES-PASFIT

2.4.1. Overview of project

Base isolation has emerged as one of the most effective and elegant strategies for protecting infrastructure and their contents under seismic loading, both in the context of new construction and in the retrofit of existing systems. The benefits of base isolation are twofold: first, by increasing the fundamental period of vibration and adding damping, the structural response is shifted into a more favourable regime and overall forces are lowered, and second, by changing the mode shape of the structure, displacement is concentrated into the isolation layer, greatly minimising storey drifts.

However, understanding of the performance of isolated buildings is primarily based on component level testing of new isolation bearings. Less well understood is the performance of large groups of isolators,

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each of which may have a slight variation in properties within the allowable design limits. Furthermore, interaction with the sub- and superstructure have the potential to change the demands on the bearing. On top of this, it is understood that the long-term behaviour of a base isolation system may differ significantly from its original as-designed behaviour. While this has been explored on rare occasions for individual aged bearings, generating sparse data points, there are no previous studies testing system-level aged isolated buildings.

ERIES-PASFIT will conduct full-scale in-situ testing of buildings, base isolated via laminated rubber bearings and friction pendulum (FP) systems that have been in service for approximately 15 years. The results of these field tests will be the first of their kind, and will be used to fill important research gaps pertaining to the characterization of the response and performance of base isolated buildings, including aspects of system-level response in conjunction with aging, deterioration and, more generally, variability of the mechanical properties of the isolation devices. Thus, this will have important implications on base isolation design, assessment and modelling strategies.

2.4.2. Experimental activities to date

The ERIES-PASFIT project has successfully completed its primary phases, focusing on the evaluation and performance assessment of base-isolated structures. The project began with identifying and characterizing case-study buildings in collaboration with local authorities and the EUCENTRE team, collecting essential data such as base isolator properties, structural layouts, and material details. Non-linear numerical analyses were conducted to assess the nominal as-designed response and theoretical aged response of these buildings (see Figure 4), using empirical aging factors from the literature. Subsequently, an in-situ testing setup was designed and implemented based on numerical simulation results. Preliminary activities, including system configuration programming and interface component production, ensured the readiness of the testing setup. In-situ testing of the case-study building was conducted, employing quasi-static reversed cyclic and dynamic loading protocols. Currently, the project is processing experimental results to assess the impact of bearing aging on structural and non-structural performance, validating findings through comparisons between numerical and experimental outcomes, and evaluating the applicability of existing design and modelling recommendations.

Figure 4. Rendering of building typology in L'Aquila, Italy considered for ERIES-PASFIT

3. Overall impacts within ERIES Research Goals

The collective efforts of these individual projects under the ERIES initiative have made substantial contributions towards its overarching research goals, particularly in advancing knowledge, testing, and developing guidelines for seismic resilience and mitigation in structural engineering. The research goals for earthquake hazards in the ERIES project focus on three primary objectives:

- First, the project aims to advance loss-driven design and mitigation approaches by addressing gaps in current seismic design and retrofit methods, emphasizing loss-based assessments and performance optimization. This includes experimental testing and database development using

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cutting-edge facilities, such as shake tables and wind tunnels, to reduce risk in buildings, critical infrastructure, and industrial facilities.

- Second, ERIES emphasizes risk quantification and prioritization to improve societal resilience and robustness. This involves probabilistic seismic and wind risk analysis, addressing soil-structure interaction effects, and developing systemic approaches for interconnected infrastructure networks, enabling better preparedness and prioritization of interventions.
- Third, the project integrates green and sustainable development across its activities by promoting innovative materials and designs that reduce environmental impact and improve energy efficiency. Examples include recycled materials for seismic isolation and testing renewable energy solutions like wind turbines and photovoltaic systems, contributing to a resilient, low-carbon built environment.

The ERIES-RESTORING project has significantly advanced understanding in the seismic assessment and retrofitting of rubble stone masonry buildings, which are particularly vulnerable to earthquakes due to their lack of specific seismic provisions. Through a comprehensive experimental campaign involving cyclic tests under various retrofit and loading conditions, the project contributes toward developing guidelines for CRM retrofit solutions. These outcomes directly support Research Goal 1 (Loss-driven Design and Mitigation Approaches) by providing critical insights into effective retrofit strategies that could reduce seismic risk for a wide range of structures, from residential buildings to historical landmarks.

ERIES-ENFRAG addresses both Research Goal 1 and Research Goal 2 (Risk Quantification and Prioritization) by experimentally examining masonry infills, a common feature in European buildings, especially in the Mediterranean region. The project's experimental tests, which include developing fragility functions for these infills, are essential for assessing in-plane (IP) and out-of-plane (OOP) behaviour under seismic loading. This work aids in understanding seismic vulnerabilities and advancing models that quantify and prioritize risks for better mitigation strategies.

The ERIES-SUPREME project focuses on the seismic vulnerability of gable walls in URM low-rise buildings, structures highly susceptible to out-of-plane motion. The experimental campaign and blind-prediction contest contribute to Research Goal 1 by enhancing understanding of gable wall capacity and interactions with roof structures, which are critical to seismic resilience. The project also aligns with Research Goal 3 (Green and Sustainable Development) by evaluating a timber-based retrofitting technique, encouraging the use of environmentally sustainable materials over conventional concrete solutions in seismic strengthening.

ERIES-PASFIT uniquely contributes to Research Goal 1 by conducting pioneering tests on the in-situ behaviour of aged, seismically isolated buildings. The project also addresses Research Area 2 (Critical Infrastructures) as it examines base isolation technology used in critical facilities. By characterizing long-term performance and advancing design and assessment strategies, PASFIT provides valuable insights into how seismic isolation systems perform over time, ensuring that buildings meet or exceed design standards in real-world conditions.

Collectively, these projects reinforce ERIES' mission by driving forward the scientific understanding, risk management, and sustainable practices required to mitigate the impact of natural disasters on the built environment. The experimental results generated through these projects not only enhance current seismic assessment methodologies but also lay the groundwork for more resilient, sustainable construction practices across Europe.

4. Summary

This paper presents the ongoing experimental activities and findings of the ERIES project to advance seismic design, assessment, and resilience through cutting-edge experimental testing and international collaboration. Utilizing world-class facilities like 9DLAB and MOBILAB at the EUCENTRE Foundation, the initiative addresses critical gaps in seismic performance knowledge and sustainable retrofitting techniques. Key projects include the seismic retrofitting of masonry buildings (ERIES-

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RESTORING), cumulative damage assessment of masonry infills (ERIES-ENFRAG), dynamic testing of vulnerable masonry gables (ERIES-SUPREME), and the long-term performance evaluation of base-isolated buildings (ERIES-PASFIT). These efforts contribute to loss-driven design, risk quantification, and sustainable development, fostering more resilient and environmentally friendly infrastructure while enhancing seismic risk mitigation across Europe.

Acknowledgements

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