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Combining Seismic Resilience and Energy Efficiency: A Retrofit Strategy for Some Historic Masonry Aggregates in Molise

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Abstract

The existing building stock in Italian historic centres predominantly comprises masonry aggregates constructed before the introduction of seismic design codes. These buildings often feature irregular geometries and low-quality materials, making them highly susceptible to seismic events. Understanding their structural behaviour is essential for developing effective and sustainable mitigation strategies that not only improve seismic performance but also meet the energy efficiency requirements outlined in recent European directives aimed at reducing carbon emissions.

This study focuses on three municipalities in the Molise region, namely Baranello, Campochiaro, and Colle d'Anchise, analysed through the CarTiS survey form. A detailed typological and structural classification of the building stock was conducted, and a representative aggregate was selected in each municipality for in-depth mechanical investigation.

Initially, the "as-built" condition of each aggregate was modelled. Subsequently, an innovative retrofitting solution was proposed: a lightweight aluminium alloy exoskeleton integrated with insulating sandwich panels. This intervention aims to enhance both seismic resilience and energy efficiency, offering a sustainable retrofit approach.

Nonlinear static and dynamic analyses were performed using a macro-element modelling strategy to evaluate the structural response under seismic loading for both the original and retrofitted configurations. The results demonstrate the effectiveness of the proposed system, showing improvements in strength and stiffness and a significant reduction in displacements during seismic events.

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1. Introduction

Masonry clustered buildings define the architectural landscape of Italian historic city centres and represent the most prevalent typology within the existing building stock. Their widespread presence dates back to the Middle Ages, a period marked by rapid and often unplanned urban expansion in response to increasing population demands. As a result, these building aggregates developed without comprehensive planning, emerging through successive construction phases over time. Built long before the introduction of modern technical codes, these structures were designed solely to withstand gravitational loads, with no consideration for seismic resistance [Bernardini et al., 2019; Acito et al., 2023; Di Trapani et al., 2024].

Each structural unit—defined as an individual building within a masonry compound exhibiting homogenous characteristics—was typically constructed during different historical periods. This has led to considerable heterogeneity in masonry texture, floor levels, and the arrangement of openings and staircases. Such irregularities significantly increase seismic vulnerability, a condition further worsened by decades of insufficient maintenance [Valente et al., 2019; Formisano and Chieffo, 2023]. This fragility has been clearly exposed by several major earthquakes over the past two decades, which have caused extensive damage to residential buildings, heritage structures (e.g., churches and bell towers), and industrial facilities. A notable example is the 2012 Emilia-Romagna earthquake, which resulted in significant economic losses [Grillanda et al., 2020].

To address the seismic vulnerability of masonry aggregates, various assessment methodologies have been proposed. Empirical approaches, often applied in large-scale evaluations, offer simplicity and efficiency, while numerical models enable detailed analysis at the individual-building level. Hybrid methods that integrate both strategies are increasingly adopted. The suitability of each approach depends on study scale, data availability, and desired accuracy. Crucially, access to geometric, structural, and historical data is essential for a reliable assessment of seismic performance [Cocco et al., 2019; Angiolilli et al., 2021; Cima et al., 2021].

Beyond their structural limitations, these buildings also suffer from significant energy inefficiency due to the widespread use of materials with poor thermal performance, as evidenced by recent survey data. Since the construction sector contributes approximately 30% of global greenhouse gas emissions, the European Union has enacted a series of regulations aimed at reducing energy consumption and environmental impact. One key milestone is the European Green Deal, launched in 2020, which promotes renovation strategies targeting both energy and environmental sustainability (E.C., 2019).

In this context, integrated seismic-energy retrofitting solutions offer a promising pathway for enhancing both safety and energy efficiency. Among these, systems combining lightweight metal exoskeletons with insulating sandwich panels are particularly effective. These solutions improve structural performance by fostering box-like behaviour under seismic loads while simultaneously reducing thermal dispersion from the building envelope [Formisano, 2022; Davino et al., 2022].

Building upon these premises, the present study investigates the seismic vulnerability of three representative masonry aggregates located in the municipalities of Baranello, Campochiaro, and Colle d’Anchise in the Molise region of Southern Italy. Geometric and structural data were collected using the CarTiS survey form, developed by the Italian Department of Civil Protection in collaboration with the Plinius Center [Zuccaro et al., 2015]. Nonlinear static and dynamic analyses were performed on the as-built configurations, confirming substantial seismic vulnerabilities. To mitigate these deficiencies, an integrated external retrofitting system was proposed, combining a lightweight exoskeleton with thermal insulation panels. Repeating the analyses on the retrofitted models demonstrated significant improvements in both seismic performance and energy efficiency. Finally, mechanical-based fragility curves were developed, highlighting a notable reduction in the probability of reaching the highest damage states.

2. The three municipalities in the Molise Region of Italy: historical background and main results from the CarTiS form

The three investigated municipalities, Baranello, Campochiaro, and Colle d’Anchise, are situated in the province of Campobasso, within the Molise region, a small area in South Italy. Their geographical locations and top-view representations are illustrated in Fig. 1. For each municipality, a representative masonry aggregate was selected based

on the available geometric surveys. The seismic performance of each aggregate was then assessed in both its original (as-built) condition and following the application of a lightweight, integrated retrofitting solution.

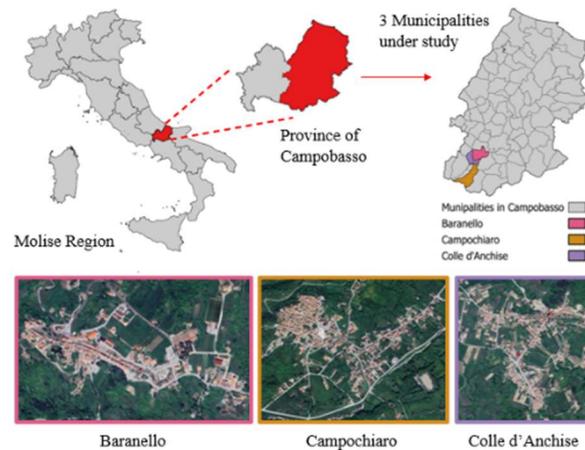


Fig. 1. Individuation of three municipalities under investigation.

The application of the CarTiS survey forms to the selected municipalities in the Molise region—of which only the main results are reported here—provided a comprehensive overview of the typological and structural characteristics of the existing building stock in their historic centres. In all three cases, a high level of seismic vulnerability was identified, attributed both to the age of the buildings and to the construction techniques employed prior to the adoption of seismic design standards.

Baranello is a municipality of Samnite origin, with its earliest settlements dating back to the 11th century B.C. The medieval village developed primarily for defensive purposes, as evidenced by the presence of the Ruffo Castle. Today, the town retains its characteristic medieval urban fabric, marked by narrow streets and stone masonry buildings. The historical core remains compact, surrounded by more recent urban expansions. Survey data revealed that approximately 60% of the buildings were constructed before 1919. Most consist of two or three above-ground storeys with small floor plans. The survey also highlighted not only a general lack of maintenance but also the absence of proper connections between floors and walls—factors that contribute significantly to seismic vulnerability. According to the EMS-98 classification, the existing building stock in Baranello falls primarily within the highest vulnerability classes (A and B) [Grünthal, 1998].

The aggregate selected for analysis in Baranello (Fig. 2a) comprises three structural units arranged across two storeys. The vertical structures are composed of roughly cut stone masonry, the predominant material in the local historical context. Intermediate floors consist of steel beams with hollow brick infill, and the double-pitched roofs are supported by timber beams.

Campochiaro is located at the base of the Matese mountains, overlooking the Biferno valley. Like Baranello, it dates back to the medieval period (9th–10th centuries), with fortifications including towers and defensive walls still visible today. The historic centre is organized around a radial plan extending from the original fort, while newer developments display a less regular urban layout. CarTiS data revealed a scenario similar to Baranello: a large proportion of the buildings were constructed before 1919, with typical typologies consisting of two or, at most, three storeys and limited floor area. Rough stone masonry accounts for 86% of the structures, and the lack of box-like behaviour is again apparent. Most buildings fall within EMS-98 vulnerability class A.

The second selected aggregate (Fig. 2b) consists of six structural units built in continuity along a sloped terrain, resulting in different internal floor elevations. Structural units SU1 and SU2 have three storeys, while the remaining units have two. As in Baranello, the vertical elements are made of rough stone masonry, intermediate floors consist of steel beams and hollow brick blocks, and the roofs are supported by timber structures.

Colle d'Anchise, the third municipality, is located on a small hill within the Matese range. It, too, originated during the Middle Ages and exhibits the characteristic layout of a fortified settlement. Compared to the other two

municipalities, Colle d’Anchise displays a broader range of construction periods: 30% of its buildings predate 1919, while 48% were built between 1920 and 1945. Although rough stone masonry remains the most common material (74%), a small number of more recent reinforced concrete structures are also present. This variety contributes to a generally lower seismic vulnerability, with most buildings falling within EMS-98 vulnerability classes B and C.

The third analysed aggregate (Fig. 2c) includes five structural units, each with two storeys. While SU2 and SU3 are constructed from rough stone masonry, the remaining units feature vertical structures built with split stone masonry.

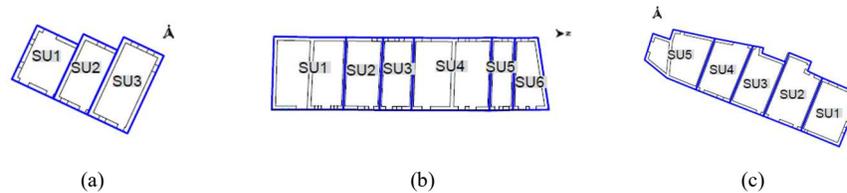


Fig. 2. Ground Floor Layout of the three case studies in: a) Baranello; b) Campochiario; c) Colle d’Anchise.

3. The combined seismic-energy coating system: components and implementation in the numerical model

The MIL15.s system, proposed for the retrofitting of the three masonry aggregates, represents an innovative solution aimed at enhancing both the seismic and energy performance of existing buildings. Developed by TM Group S.r.l. and patented in 2022, this technology belongs to the category of external structural coating systems and is distinguished by its dual objectives: improving seismic response and reducing thermal dispersion, all through a minimally invasive and rapid-installation approach.

The system is based on the installation of a metal exoskeleton composed of extruded aluminium alloy elements. Vertical aluminium profiles are anchored to the perimeter masonry walls using chemical anchors. Between these profiles, thermal insulating sandwich panels are inserted; these are composed of trapezoidal steel sheets enclosing an insulating core, which can consist of mineral wool, polyurethane, or sustainable materials such as cork or hemp. The assembly is completed by an external aluminium profile, fastened to the outer steel sheet using self-drilling screws.

As illustrated in Fig. 3, the components of the system are designed in compliance with Eurocode 9 and the CNR-DT 208/2011 guidelines. This configuration enables the retrofitted building to exhibit box-like structural behaviour, significantly mitigating the risk of out-of-plane failure (EN 1999-1-1, 2022; CNR-DT, 2011).

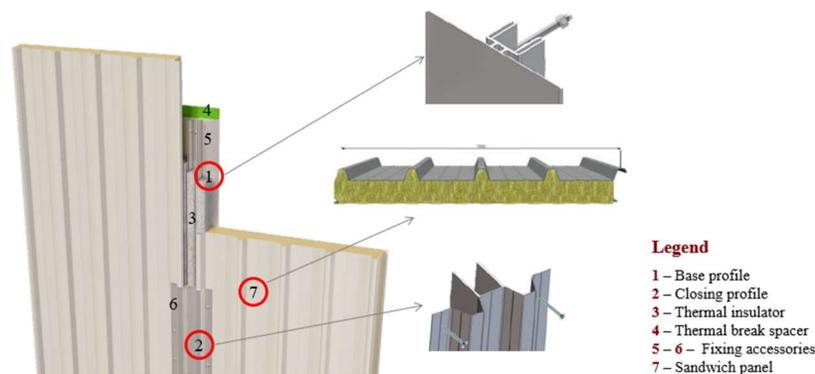


Fig. 3. View of the MIL15.s integrated retrofit system.

4. Seismic vulnerability assessment of three masonry compounds

4.1. Modelling through FME approach

The seismic vulnerability assessment was conducted by developing frame-by-macro-element models using the 3Muri software, a widely adopted and recognized tool for the analysis of existing masonry buildings. All models, shown in Fig. 4, were constructed based on the lowest level of knowledge (KL1), with an associated confidence factor of 1.35, in accordance with the Italian Technical Standards (MD, 2018; MC, 2019).

For the retrofitted models, the presence of the combined coating was represented by modelling the sandwich panels as equivalent diagonal braces with a full circular cross-section. The models also accounted for the additional load introduced by the exoskeletons, which remains relatively limited due to the lightweight properties of the aluminium alloy material.

Under these assumptions, the rough stone masonry was characterized by a tensile strength (f_m) of 2.00 N/mm², a shear strength of 0.035 N/mm², a Young's modulus (E) of 1230 N/mm², and a shear modulus (G) of 410 N/mm².

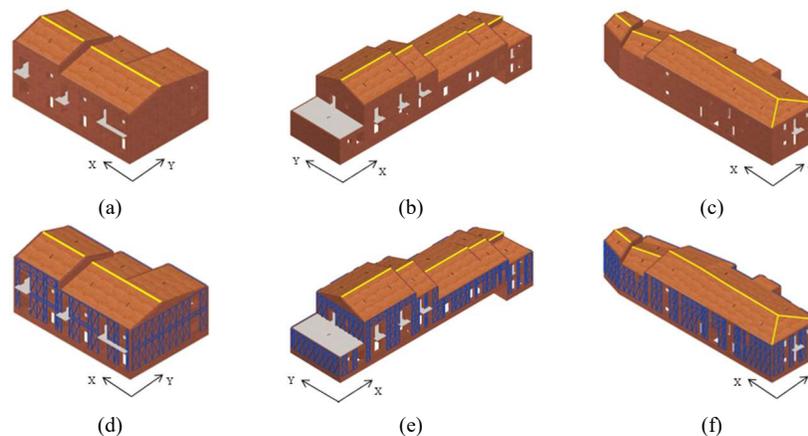


Fig. 4. FME models: As-built aggregates in a) Baranello, b) Campochiario and c) Colle d'Anchise and Retrofitted aggregates in d) Baranello, e) Campochiario and f) Colle d'Anchise.

Following the development of the models, both nonlinear static and dynamic analyses were performed to gain a comprehensive understanding of the seismic performance of the three masonry aggregates.

Nonlinear static analyses (pushover analyses) were carried out by monitoring the displacement of a control node placed at the top of the structure, located at the barycentre of mass and stiffness. Two different lateral force distributions were applied, and the results were evaluated using the α_{SLV} coefficient, defined as the ratio between the capacity and demand peak ground acceleration (PGA), as well as through the analysis of capacity curves (base shear vs. top displacement).

For the nonlinear dynamic analyses, accelerograms—representing ground acceleration time histories—were obtained from the Rexel web platform. This freely accessible tool generates ground motion records based on user-defined parameters, such as the latitude and longitude of the reference site. The selected accelerograms are spectrum-compatible, meaning they closely match the target design spectrum, although they may not be associated with seismic events that occurred near the site itself.

In total, seven seismic events were selected, each comprising two orthogonal horizontal components (typically aligned along the North-South and East-West directions) from the same seismic record. This bidirectional input allows for a more realistic simulation of ground motion effects on the structural response.

4.2. Comparison of the results: As-built vs Retrofitted Configurations

Based on the results obtained from the nonlinear static analyses (NLSA), Table 1 presents the calculated seismic safety coefficients. In all three case studies, the application of the integrated seismic-energy coating system resulted in a notable increase in these indices.

The aggregate located in Campochiaro satisfies the seismic performance improvement requirements established by the Italian Technical Code in both principal directions. In contrast, the third case study (Colle d’Anchise) achieves compliance only in the longitudinal direction. The first masonry aggregate (Baranello), however, falls short of the required improvement thresholds in both directions, despite the observed enhancement in seismic response.

Table 1. Results of the non-linear analyses in terms of seismic safety index.

Aggregate	Seismic Dir.	Seismic Load	As Built Conf. α_{SLV}	Retrofitted Conf. α_{SLV}	Δ [%]
Baranello	-X	Static Forces	0.319	0.365	4,6
	-Y	Static Forces	0.414	0.496	8,2
Campochiaro	+X	Static Forces	0.471	0.584	11,3
	-Y	Static Forces	0.361	0.628	26,7
Colle	-X	Uniform	0.738	0.878	14
	+Y	Static Forces	0.475	0.548	7,3

Fig. 5 compares the capacity curves of the three masonry aggregates. In all cases, the dotted lines representing the as-built condition lie below the curves corresponding to the retrofitted configurations. This confirms that the proposed retrofitting system significantly enhances both strength and stiffness, enabling the structures to withstand higher base shear forces.

In some instances, such as the Baranello aggregate, increased displacements are also observed, indicating improved ductility following the intervention. As expected, the aggregate in Baranello, composed of only three structural units (SUs), exhibits the lowest base shear values, primarily due to its smaller overall mass. In contrast, the aggregates in Campochiaro and Colle d’Anchise, comprising six and five SUs, respectively, achieve higher base shear capacities, reflecting the influence of their larger structural mass.

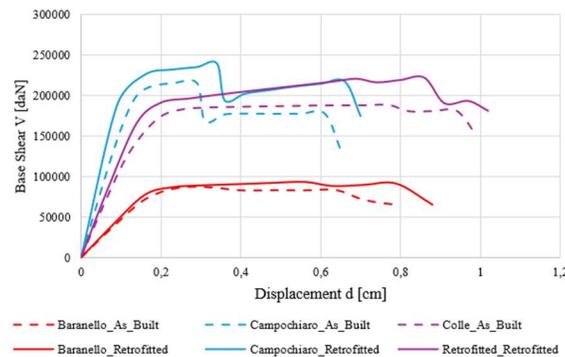


Fig. 5. Comparison of capacity curves for the three masonry aggregates along X-Direction (Legend: Continuous Lines=Retrofitted State; Dotted Lines= As-Built State).

With regard to the results obtained from the nonlinear dynamic analyses (NLDA), Fig. 6 illustrates the two most representative outcomes, corresponding to the case studies in Campochiaro and Colle d’Anchise, both of which also achieved satisfactory seismic improvement in the nonlinear static analyses (NLSA). The graphs display the time-displacement responses under actual ground motion records.

For the Campochiaro aggregate, the most favorable scenario occurs under Event 3 (Fig. 6a). In this case, the as-built configuration exhibits significantly larger displacement amplitudes compared to the retrofitted state. The latter shows a more restrained displacement response, with visibly reduced peaks and a smoother time-history profile. This

behaviour suggests that the strengthening intervention effectively increased the system's stiffness and/or energy dissipation capacity, thereby reducing deformations and enhancing overall seismic performance.

In the third case study, located in the historic centre of Colle d'Anchise (Fig. 6b), the green curve representing the retrofitted configuration generally remains below or coincides with the red curve of the as-built condition, indicating a moderate reduction in displacement. However, the benefits of the intervention appear less pronounced and more intermittent than in the Campochiaro case. There are segments where the two curves nearly overlap, suggesting that for this particular ground motion, the impact of the retrofit on peak displacements is limited.

Overall, the graphical results demonstrate the capacity of the retrofitting system to reduce displacement demands, although the extent of the improvement varies. In some cases, the reduction is substantial, while in others it is more marginal. Nevertheless, the retrofitting consistently enhances the seismic response. These findings underline the importance of case-specific evaluation, as the effectiveness of a seismic retrofit is influenced by multiple factors, including the characteristics of the ground motion (e.g., magnitude, frequency content, and duration) and the unique dynamic behaviour of the building.

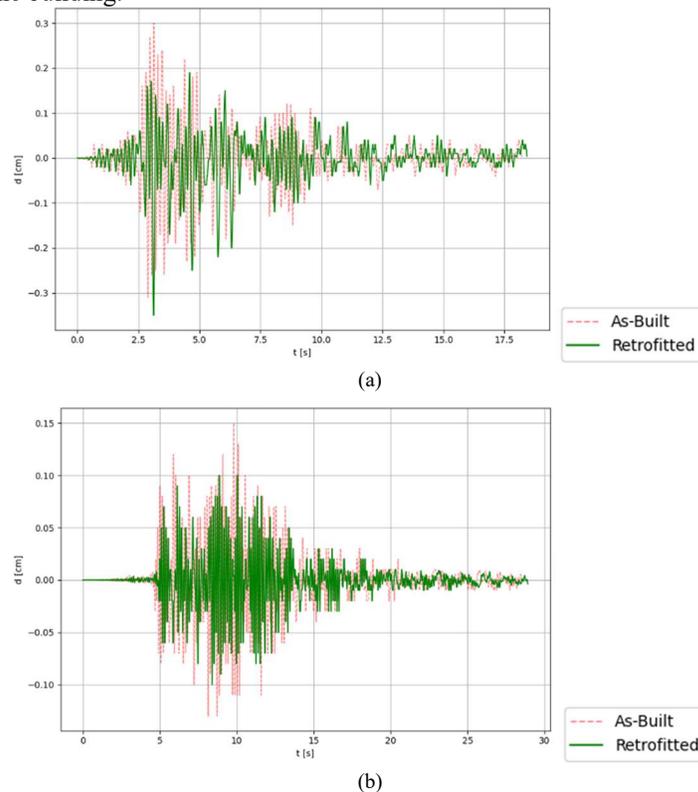


Fig. 6. Results of NLDA for two aggregates in a) Campochiaro (Event 3) and b) Colle d'Anchise (Event 2).

5. Conclusions

This study focused on the seismic assessment of three masonry building compounds and the evaluation of an innovative integrated seismic-energy retrofitting solution. The selected case studies, located in the municipalities of Baranello, Campochiaro, and Colle d'Anchise, in the province of Campobasso (Molise region of Italy), represent typical examples of historical masonry aggregates in South Italy. A preliminary typological and structural investigation was conducted using the CarTiS survey form. This assessment provided a comprehensive overview of the existing building stock. The data revealed that most of the buildings were constructed before 1919 using rough stone masonry and had undergone minimal maintenance or strengthening. As a result, the buildings exhibited high seismic vulnerability, with most classified within EMS-98 vulnerability classes A and B.

The seismic performance of the three selected aggregates was analysed in both as-built and retrofitted configurations through frame-by-macro-element modelling. The proposed retrofit solution consisted of an external seismic-energy coating system designed to simultaneously enhance seismic capacity and thermal performance. This system includes a lightweight aluminium alloy exoskeleton coupled with sandwich panels featuring insulating cores, offering benefits such as corrosion resistance, structural reinforcement, and thermal efficiency.

The outcomes of both nonlinear static and dynamic analyses provided compelling evidence of the retrofit's effectiveness. Pushover analyses showed a marked increase in seismic safety coefficients for all case studies, with two aggregates achieving the seismic improvement thresholds established by the Italian Standard. Nonlinear dynamic analyses, using real ground motion records, further demonstrated the system's ability to reduce displacement demands, confirming its beneficial impact on the structural response.

Overall, the results highlighted the potential of the proposed integrated system not only to improve seismic resilience but also to promote energy efficiency in historic masonry buildings.

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