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ORIGINAL ARTICLE

Seismic fragility and energy efficiency upgrading of masonry compounds using lightweight aluminium alloy exoskeletons: a case study in South Italy

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Abstract

The seismic and energy retrofitting of existing masonry structures is a critical area of focus in structural engineering, particularly since a significant portion of the current building stock was constructed before the adoption of modern seismic codes. Consequently, these buildings not only lack seismic resilience but also experience considerable heat loss due to the use of materials with poor thermal performance. Recent seismic events across Europe, along with European directives, have highlighted the inadequacies of these structures and the urgent need for interventions that address both structural reinforcement and energy efficiency. Integrated solutions that simultaneously tackle these challenges offer a cost-effective and time-efficient approach to retrofitting. In this context, modern coating systems emerge as a promising alternative. By combining a metal frame base with thermal insulation materials, these systems enhance both seismic resistance and energy performance with minimal invasiveness. This paper explores the application of an external coating system, featuring aluminium alloy exoskeletons and insulating sandwich panels, to a masonry building complex in Castelpoto, a small town in the province of Benevento, located in the heart of the Campania region. The study first evaluates the performance of the existing compound through a macroelement modelling approach, followed by the arrangement of a lightweight retrofitting solution designed to improve the building's seismic response and promote the box-like structural behaviour. The findings demonstrate that the integrated retrofitting system leads to higher safety factor values, which result in an overall improvement in seismic performance. These benefits are further confirmed by a fragility study, which shows a significant reduction in the probability of exceeding critical damage thresholds. The results highlight the effectiveness of the proposed solution in improving both seismic resilience and energy efficiency.

Keywords Masonry clustered buildings · Integrated seismic-energy interventions · Seismic coat · Aluminium alloy exoskeleton · Fragility curves

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1 Introduction

1.1 Vulnerability and retrofit of masonry aggregates

Recent seismic events in medium-to-high hazard areas of Italy and Europe have underscored the vulnerability of existing building stock, particularly in historic centres dominated by unreinforced masonry structures (Grillanda et al. 2020; Angiolilli et al. 2021; Formisano et al. 2021; Khemis et al. 2023). A substantial portion of these buildings exists in aggregates formed through centuries of urban development and architectural layering, beginning in the Middle Ages (Longobardi and Formisano 2022).

Within these aggregates, individual units often share boundary walls but lack adequate connections to adjacent structures, resulting in the absence of box-like behaviour. This structural weakness predisposes them to local collapse mechanisms. Additionally, the phased construction of these units has led to significant variability in masonry types and construction techniques, reflecting their respective periods. Discrepancies in height, inter-story dimensions, roof configurations, openings, and staircase placements are common (Valente et al. 2019). Most critically, these structures were not designed to withstand seismic forces, as they were originally built to bear only their own weight.

Assessing the seismic vulnerability of such heterogeneous complexes is particularly challenging due to these factors. Accurate evaluation requires comprehensive knowledge of geometric layouts, materials, and any previous consolidation interventions. Furthermore, interactions between individual units within the aggregate are complex and difficult to model accurately using advanced software (Bernardini et al. 2019).

Despite these challenges, considerable progress has been made in developing reliable analysis techniques. A range of approaches—empirical, mechanical, and hybrid—now supports both large-scale assessments and detailed analyses of individual buildings (Onescu et al. 2023).

Beyond structural vulnerabilities, these historic buildings typically exhibit poor energy performance. Most fail to meet modern thermal comfort standards due to significant heat loss and cold infiltration caused by highly conductive materials and construction defects, such as thermal bridges. As a result, many fall into the lowest energy efficiency class (Class G), leading to elevated energy costs (Heat Roadmap Europe, 2017; ED 2018/844; Pohoryles et al. 2020, Pohoryles et al. 2022).

Addressing these dual challenges—seismic retrofitting and energy efficiency—requires urgent, integrated interventions. European regulations mandate reductions in thermal dispersion to curb CO_2 emissions, identifying the construction sector as a major contributor (European Commission 2019; United Nations Environment Programme 2020; The White House 2021). Simultaneously, compliance with modern technical standards is essential to ensure structural safety.

Traditional methods typically address seismic and energy performance separately. For example, metal tie rods can be installed to prevent overturning, and consolidation injections can strengthen masonry. However, integrated solutions that simultaneously enhance seismic resilience and energy efficiency are more efficient and cost-effective.

One promising approach is the use of external envelope systems (Davino et al. 2022; Formisano 2022). This innovative technology enables rapid retrofitting by combining a metal base frame to absorb seismic forces with insulating panels to reduce thermal dispersion. Such systems are versatile and can be applied to various structures, including masonry and reinforced concrete (Meglio et al. 2023).

This paper evaluates the seismic behaviour of a typical unreinforced masonry aggregate retrofitted with an integrated seismic–energy coating system. The study begins with an overview of the urban context in which the masonry compound is situated, before shifting focus to the aggregate itself, identifying its seven structural units and the materials used in both vertical and horizontal components. Following this preliminary analysis - recommended by the Standard Code for a comprehensive vulnerability assessment - the proposed retrofitting system is introduced, detailing its components, functionality, and key advantages. The study then progresses to the modeling phase, where the behavior of the original "as-built" configuration is analyzed and compared to the retrofitted model, highlighting the improvement in seismic safety coefficients. Finally, the paper presents a comparative analysis of the pre- and post-intervention states through both empirical and mechanical fragility curves. The findings indicate that the installation of the integrated seismic-energy coating system significantly reduces the probability of exceeding damage thresholds, particularly at higher damage levels.

1.2 Research significance

The topic investigated in this study remains relatively underexplored in the existing scientific literature, primarily because it focuses on innovative structural retrofitting systems that have only recently entered the construction market. Most research on seismic retrofitting and energy-efficient interventions has approached these challenges separately, leaving a gap in understanding how integrated solutions can effectively address both aspects simultaneously.

This study aims to bridge that gap by demonstrating how an integrated technique can enhance both the seismic performance and thermal efficiency of existing masonry buildings. This approach offers multiple advantages, optimizing resources and reducing intervention costs while providing a more sustainable and efficient alternative to traditional reinforcement methods that focus solely on structural strengthening.

The key contribution of this research lies in presenting a dual-benefit solution that advances the state of the art in building retrofitting. Unlike conventional techniques, this approach balances structural reinforcement with energy efficiency, offering a comprehensive response to modern building challenges. Additionally, the findings expand the body of knowledge on innovative retrofitting solutions, providing practical insights for engineers and designers engaged in rehabilitation projects.

However, the proposed technique is currently applicable only to existing masonry buildings that are not classified as cultural heritage sites or subject to preservation constraints. Despite this limitation, the study establishes a valuable foundation for future retrofitting strategies that could be adapted to a broader range of structures, potentially paving the way for more flexible and widely adopted integrated retrofitting solutions.

2 The investigated masonry compound

2.1 The historic centre of Castelpoto

Castelpoto is a small town situated in the province of Benevento, in the Campania region of Italy. Nestled in the hilly Sannio area, the town offers a scenic view of the Calore River Valley, which has historically supported its growth through agriculture. Covering an area of approximately 17.4 square kilometers, Castelpoto has a population of fewer than 1,500 residents.

Figure 1 illustrates the town's location and provides a top-down view of its layout.

The origins of Castelpoto are challenging to pinpoint precisely. Archaeological evidence indicates Roman activity in the area, but the town's current location is primarily attributed to the Longobards, a Germanic people who settled in the Benevento region during the Middle Ages. Under Norman rule, the construction of Castelpoto's castle and the establishment of its initial urban settlements began. Subsequent rulers, including the Swabians, Angevins, and Aragonese, further enhanced the town's significance due to its strategic location.

Castelpoto began to decline in the late 19th century, following the unification of Italy. Economic difficulties during this period prompted widespread emigration, a trend that intensified throughout the 20th century. The town's vulnerability to earthquakes exacerbated this decline, as several devastating seismic events caused extensive building collapses and accelerated depopulation.

In recent years, after a prolonged period of abandonment, Castelpoto has begun to recover through a gradual process of reconstruction and revitalization.

2.2 Geometric and structural properties of the case study

To assess the benefits of the integrated retrofit solution, a masonry aggregate from the town of Castelpoto was selected for analysis. The compound is located slightly off-center relative to the main urban area, but it falls within a zone shaped by urban transformations, heavily influenced by the presence of the medieval castle. Given its historic and architectural significance, the compound requires careful preservation and protection.

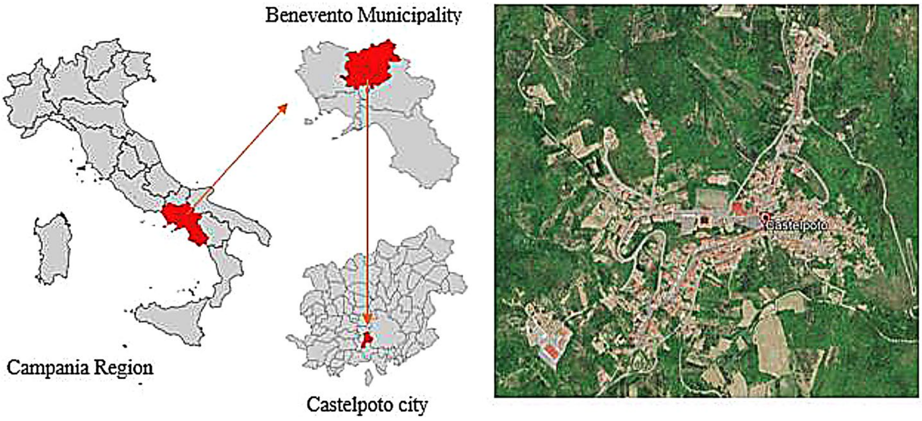


Fig. 1 Geographic location of Castelpoto city and top view of its historic centre

Figure 2 provides a top-down view of the masonry aggregate, along with a layout identifying its seven structural units.

The cells are positioned on the hillside, leading to varying heights across the structures. All buildings, with the exception of Building 7, are arranged over two storeys (Chieffo et al. 2023). Below is a brief overview of their key characteristics:

- **Structural Unit No. 1 (SU1):** This unit features vertical walls made of irregular stone, with thicknesses ranging from 50 to 55 cm. The intermediate floors consist of wooden beams and a single layer of planks. The roof is single-pitched.
- **Structural Unit No. 2 (SU2):** Characterized by vertical walls made of irregular sandstone, approximately 50 cm thick. The intermediate floors include masonry vaults on the ground floor and wooden beams on the first floor. The roof is double-pitched and constructed from wood.
- **Structural Unit No. 3 (SU3):** This unit has vertical masonry walls made of irregular stone, up to 60 cm thick, with wooden intermediate floors. The roof is double-pitched.
- **Structural Unit No. 4 (SU4):** Features perimeter walls made of irregular stone, with internal partitions later added using solid bricks. The intermediate floors consist of a mix of masonry vaults and wooden slabs.
- **Structural Unit No. 5 (SU5):** Constructed with irregular sandstone masonry, with regular sandstone blocks added in later years following seismic events. The intermediate floors consist of steel profiles and masonry vaults.
- **Structural Unit No. 6 (SU6):** Composed of irregular masonry with wooden floors.
- **Structural Unit No. 7 (SU7):** The only single-storey building in the aggregate, constructed with irregular sandstone masonry. It lacks intermediate floors, and the roof has collapsed.

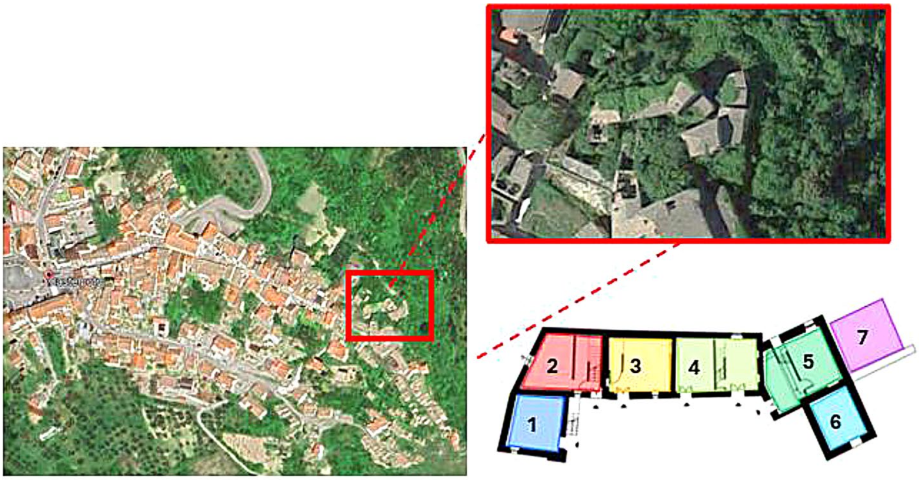


Fig. 2 The investigated clustered building: location within the city and individuation of the seven structural units

Like many other buildings in the area, this case study has suffered significant damage from various earthquakes. Some units experienced severe damage, such as partial roof collapses (e.g., Unit 7), while others sustained minor structural issues.

The photographic documentation in Fig. 3 offers a detailed view of the current state of deterioration. The masonry, no longer covered by plaster, has eroded, leading to the powdering of the mortar. The steel-beamed internal floors show signs of advanced corrosion, and the wooden beams exhibit considerable deterioration, including partial collapses and localized deflections.

The mechanical properties of the different types of masonry are reported in Table 1. For all the typologies, according to the current Italian Codes (M.D. 17/01/2018; M.C. 02/01/2019), the lowest level of knowledge (KL1) was assumed with a confidence factor equal to 1.35.

3 The innovative integrated seismic – energy coat: the MIL15.s system

3.1 Overview of the existing coating solutions

Coating systems represent one of the most effective solutions for the integrated seismic and energy requalification of existing buildings. These systems offer a versatile and innovative approach, having only recently been introduced to the construction market. Despite

Fig. 3 Photographic documentation of the crack pattern: (**a**) Crushing phenomena of vertical masonry walls; (**b**) Degraded wooden beams; (**c**) Corrosion phenomena on steel beams; (**d**) Collapse of the roof of SU7

Table 1 Mechanical properties of masonry walls

Irregular Soft Stone				
Tensile strength f_m	**Young Modulus E**	**Shear Modulus G**	**Specific weigh W**	**Shear strength τ**
[N/mm^2]	[N/mm^2]	[N/mm^2]	[kN/m^3]	[N/mm^2]
1.4	1080	360	14	0.028
Regular limestone				
Tensile strength f_m	**Young Modulus E**	**Shear Modulus G**	**Specific weigh W**	**Shear strength τ**
2.0	1410	4500	16	0.040
Solid brick				
Tensile strength f_m	**Young Modulus E**	**Shear Modulus G**	**Specific weigh W**	**Shear strength τ**
2.6	1500	500	18	0.05

their relatively recent emergence, many of these systems have already been widely adopted (Davino et al. 2022).

Some envelope systems incorporate shear walls made of cast-in-place concrete, poured between two insulating panels that also serve as formwork. One example is the Geniale Coat (https://www.ecosism.com/moduli/geniale/), patented by EcoSism®, which also developed the KarmaCoat (https://www.ecosism.com/moduli/karma/), a less invasive system. Similar ly, the Sismacoat system (https://sismacoat.it/) features a reinforced concrete exterior wall.

In addition to these heavier systems, there are lighter alternatives that use metal exoskeletons made from cold-formed steel or aluminium alloy components, combined with insulating panels to fill the spaces within the base frame. For example, the Resisto 5.9 Tube (https://www.progettosisma.it/product/resisto-5-9-tube/) from Progetto Sisma uses cold-formed galvanized steel profiles, while the Duo System envelope (https://duosystem.eu/) employs aluminium alloy components. Additionally, Betonwood (https://www.betonwood.com/betontherm-fiber.html) offers a solution that combines wood elements with insulated panels.

An overview of some existing coating systems is provided in Fig. 4

According to current Italian legislation, two approaches exist for installing seismic-energy coats: “Global Intervention” and “Local Intervention.” In the global intervention approach, metal exoskeletons are anchored to the building’s existing foundations, providing comprehensive reinforcement. In contrast, the local intervention approach involves a system where the elements are not directly connected to the foundations. Instead, it focuses on reinforcing specific sections of the building to prevent local collapse mechanisms.

The primary advantage of these retrofit systems lies in their ability to simultaneously enhance both seismic resilience and energy performance. Furthermore, these systems are quick and easy to install, which helps reduce both costs and construction time. This efficiency is achieved because the components, such as metal exoskeletons, are only connected to the perimeter masonry walls, with the elements being custom-manufactured based on a precise in-situ survey.

Since these solutions are applied externally, they are minimally invasive, making them suitable for various building types, including residential buildings, offices, and schools, where ongoing activities can continue without disruption (Longobardi et al., 2024).

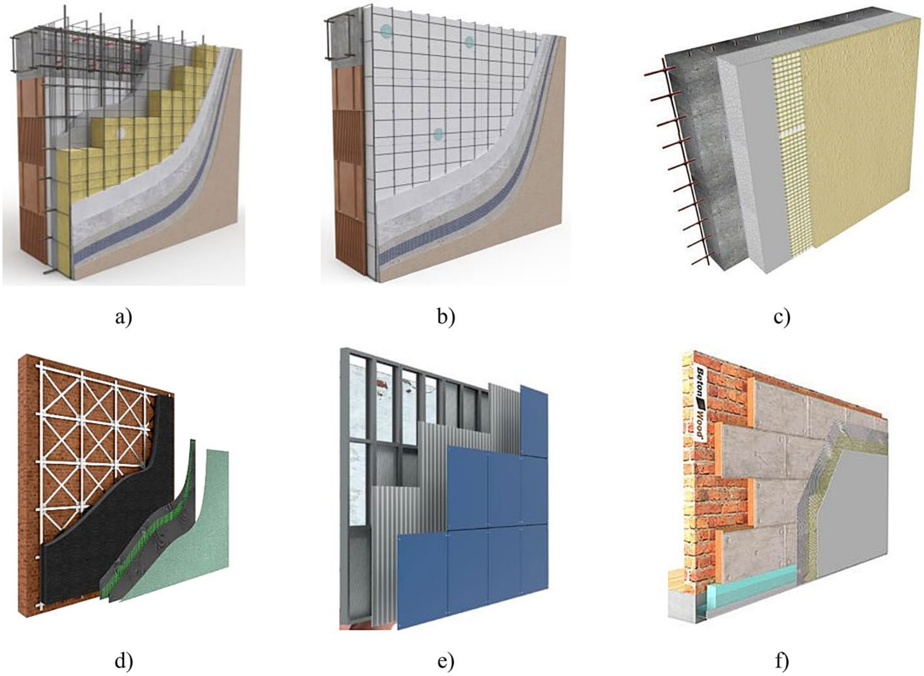


Fig. 4 Overview of the different existing coating systems. (**a**) Geniale Ecosism; (**b**) Karmacoat; (**c**) SismaCoat; (**d**) Resisto 5.9 coat; (**e**) Duo System; (**f**) Betontherm

3.2 Functioning and components

For this case study, the MIL15.s coating system by TM Group S.r.l. (https://www.tmgroupsrl.eu/sistemi-per-ledilizia/) was chosen as the integrated retrofitting solution. This system uses aluminium alloy profiles (AW6060 – T6), which are produced through an extrusion process, followed by thermal treatment and artificial aging.

While various coating systems are available on the market, the MIL15.s system introduces a more advanced and versatile approach. Unlike cast-in-place reinforced concrete coatings, which add significant weight and require extensive on-site operations, the MIL15.s envelope system is lightweight, modular, and prefabricated, enabling rapid installation with reduced labour costs and environmental disruption. This also minimizes the carbon footprint associated with the construction process.

Compared to steel-based exoskeletons, the proposed integrated solution employs aluminium alloy, which is three times lighter, reducing, as in the previous case, any additional loads on the structure. Furthermore, aluminum profiles are naturally corrosion-resistant, as a thin protective layer forms on their surface upon exposure to the atmosphere, eliminating the need for specific treatments.

Figure 5 illustrates the system and its main components.

The base profile is the first component applied to the structure (Fig. 5, Element No. 1), secured using chemical anchors (approximately 12 mm in diameter) to ensure optimal adhesion (Fig. 5, Element No. 5). After two consecutive base profiles are installed, the sandwich

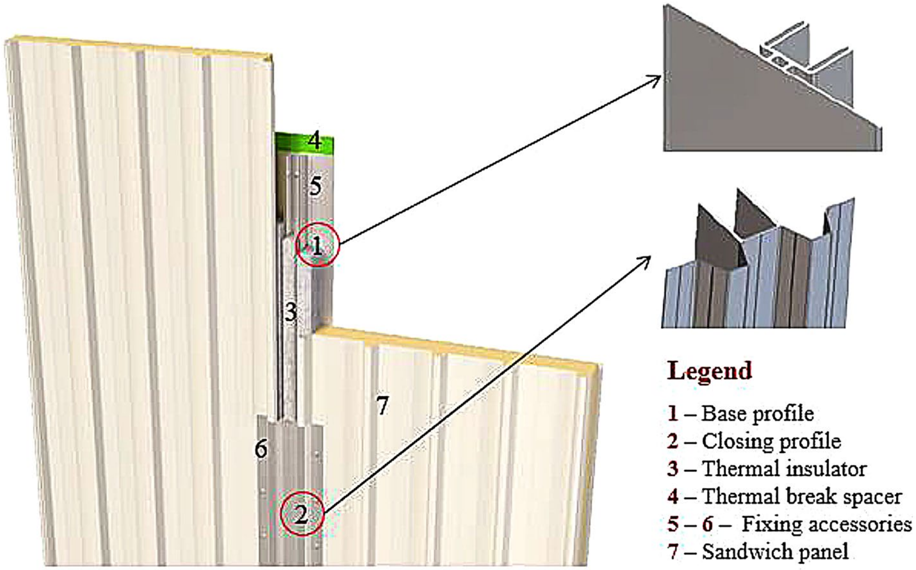


Fig. 5 Schematic view of the MIL15.s coating system with a focus on the shape of the two extruded aluminium profiles (Base and closing profiles, No. 1 and 2, respectively)

panel is placed (Fig. 5, Element No. 7). This panel features double trapezoidal sheeting and is fixed in position with self-drilling screws (5.5 mm in diameter).

The interior of the sandwich panel can be filled with synthetic materials such as polyurethane or rock wool, or with natural insulating products like cork, hemp, coconut, linen, or straw fibres, depending on the desired performance and sustainability.

The MIL15.s system is completed with closing profiles (Fig. 5, Element No. 2), which are anchored to the external sheeting of the sandwich panel using screws (Fig. 5, Element No. 6), providing the final layer of protection and reinforcement.

3.3 Economic feasibility and cost comparison

The MIL15.s system has an initial cost of approximately €200 per square meter, which includes the supply and installation of both the aluminum alloy exoskeleton and insulating sandwich panels. This price is comparable to that of traditional reinforcement techniques, which now also incorporate composite materials such as FRP, FRCM, and others.

However, while composite materials primarily enhance a building's mechanical strength, often with little impact on thermal performance, the MIL15.s system provides a dual benefit: it strengthens the structure by promoting box behavior while also delivering thermal insulation. This combined functionality makes it a more comprehensive solution for both energy efficiency and structural integrity.

Though the upfront cost of the MIL15.s system may seem high, it proves to be cost-effective in the long run. Its thermal efficiency significantly reduces heating and cooling costs, allowing the initial investment to be offset over time. Additionally, the aluminum framework combined with insulating panels ensures durability and long-lasting performance, reducing maintenance expenses and extending the lifespan of the installation.

In many countries, adopting energy-efficient retrofitting solutions like the MIL15.s system is supported by financial incentives, tax deductions, or government subsidies, making the initial investment more accessible. European regulations actively promote energy-efficient renovations to achieve carbon reduction goals, often accompanied by financial support programs.

In Italy, in recent years, specific measures have been introduced to encourage interventions aimed at reducing seismic risk and improving energy efficiency. Among these, the Sismabonus and Superbonus stand out, offering substantial tax deductions for both seismic improvements and energy-efficient retrofitting, further increasing the economic viability of such interventions.

The Superbonus 110%, introduced with the "Decreto Rilancio" (Law Decree No. 34/2020), offers significant financial support for interventions carried out by December 31, 2025, in municipalities located in areas affected by seismic events since April 1, 2009, where a state of emergency has been declared. This incentive covers both seismic and energy-efficiency improvements, making it ideal for interventions like the MIL15.s system, which provides dual benefits.

Regarding the Sismabonus, initially introduced by Law Decree No. 63/2013, the 2025 Budget Law modifies the incentives, establishing a tax deduction to be spread over five equal annual installments:

- For expenses incurred in 2025, the deduction is 50% for interventions on primary residences and 36% for other properties.
- For the years 2026 and 2027, the deduction decreases to 36% for primary residences and 30% for other properties.

Despite the cuts and reductions in recent years, these measures continue to help reduce the initial cost of seismic and energy-efficiency retrofitting, making systems like MIL15.s more accessible and encouraging the adoption of such improvements in areas prone to seismic activity.

4 Seismic behaviour assessment

4.1 Definition of the FME model and design of the retrofitting technique

The evaluation of the "as-built" configuration revealed the inadequate seismic performance of the case study. To assess this, analyses were conducted using the 3Muri software by STA. DATA (Piccolo et al. 2022; Onescu et al. 2023). This software employs a frame by macro-element (FME) approach, which is based on observations of damage in real structures after various earthquakes. In this method, each masonry panel is divided into three elements: masonry piers, spandrels, and rigid nodes. The masonry piers and spandrels are where damage and deformability are most concentrated, while the rigid nodes are assumed to behave as infinitely rigid, offering no flexibility.

Once all the primary geometrical and structural properties of the masonry compound were defined, the next phase involved creating a model using numerical software. The initial step focused on establishing the axis of the wall, followed by the assignment of material properties to each component. Next, the horizontal floors were incorporated, with the corresponding loads applied. In addition to the self-weight, which varies depending on the type of floor (such as steel beams and clay tiles or reinforced concrete), live loads of 2 kN/m² were applied, in accordance with the residential use of the building as specified by the Italian Regulations.

Figure 6 presents the three-dimensional model of the case study, illustrating the meshed structure where the three macro-elements—piers, spandrels, and rigid nodes—are clearly identifiable.

In the subsequent phase of the analysis, the benefits resulting from the installation of the integrated seismic-energy coat were investigated. Specifically, the presence of the coat was modelled by introducing vertical elements to represent the aluminium alloy profiles, while the sandwich panel was schematized as an equivalent diagonal with a full circular cross-section.

To calculate the area of a single diagonal, the following formula was applied:

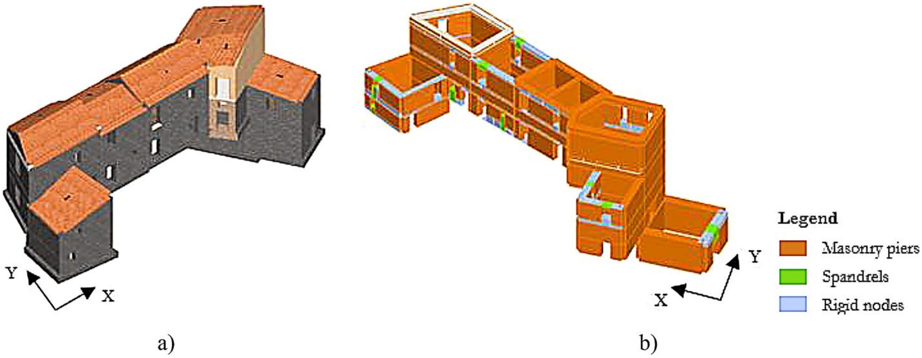
$$\mathrm{A_d} = \mathrm{K_{eq}} \cdot \mathrm{l_{eq}} / (\mathrm{E} \cdot \cos^2\alpha) \tag{1}$$

where:

- E represents the elastic modulus of the material
- l_{eq} is the equivalent length, equal to b/cosα, being b the frame width, h the frame height and α = arctg h/b.
- K_{eq} is the equivalent stiffness.

The equivalent stiffness K_{eq} of each diagonal derives from the shear flexibility of the diaphragm C' as follows:

$$\mathrm{K_{eq}} = 1/\mathrm{C'} \tag{2}$$



a) b)

Fig. 6 (**a**) Three – dimensional model; (**b**) Meshed structure with legend of macroelements

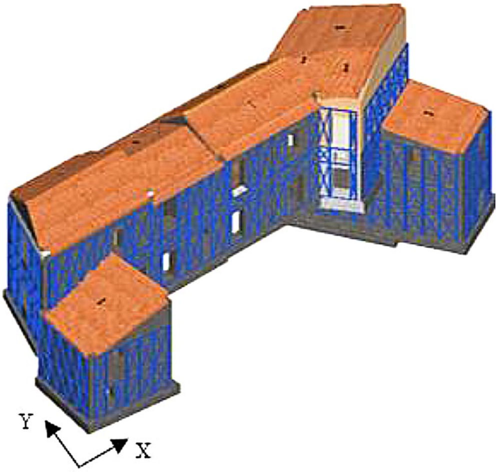


Fig. 7 Three-dimensional model of the clustered building provided with the seismic coat

Table 2 Comparison of the results before and after the retrofit intervention

Seismic Direction	Seismic Load	Before Int. α_{SLV}	After Int. α_{SLV}	Δ
+X	Uniform Distribution	0.564	0.720	27%
+Y	Uniform Distribution	0.349	0.510	46%

where C' considers different components of the shear flexibility (deformations of sheets and fasteners).

Figure 7 provides a view of the three-dimensional model equipped with the innovative retrofitting technique arranged on the facades of the entire masonry aggregate.

The creation of the retrofitted model was carried out by adding vertical profiles and diagonal bracing. The updated model also accounts for the additional weight introduced by the exoskeletons, which remains relatively limited.

It was assumed that a local intervention would be carried out, meaning the system would not be connected to the foundations of the pre-existing building. Consequently, in the software, the coating system was modelled as a reinforcement technique for the masonry panels.

4.2 Comparison of results: "As-Built" state Vs "Retrofitted" configuration

Static non-linear analyses were conducted by monitoring the displacement of a top control node. In accordance with the Technical Code (Ministry of Infrastructure and Transport), two force distributions were considered: the first was proportional to the static forces, and the second was a uniform distribution based on a homogeneous acceleration along the building's height.

The results of the analysis are presented in Table 2, where the safety coefficient α_{SLV} is calculated. This coefficient represents the ratio between the building's capacity and the demand peak ground acceleration, indicating the level of safety against seismic forces.

The outcomes highlighted that the retrofitted state achieves values more than 0.10 higher than those of the as-built condition, thus enabling the seismic upgrading as defined by the Italian Technical Standards, which serve as the regulatory reference for the entire project.

Additionally, the capacity curves (Base Shear vs. Top Displacement), shown in Fig. 8, indicate an increase in resistance, particularly pronounced along the longitudinal direction. In both cases, there is also a slight increase in ductility, resulting in higher displacements.

5 Comparison of results in terms of fragility curves

After investigating the seismic behaviour of the masonry complex through non-linear static analyses of both the as-built and retrofitted configurations, the final part of the study focuses on the development of fragility curves. This phase allows for a comparison of seismic risk between the original and reinforced configurations, providing a clear measure of the effectiveness of the proposed integrated intervention.

Fragility curves are a valuable method for assessing the safety margin of the structural system. They serve as a fundamental tool to quantify the likelihood that a specific damage level will be reached or exceeded, given a particular intensity measure (Rota et al. 2010; Asteris et al. 2019).

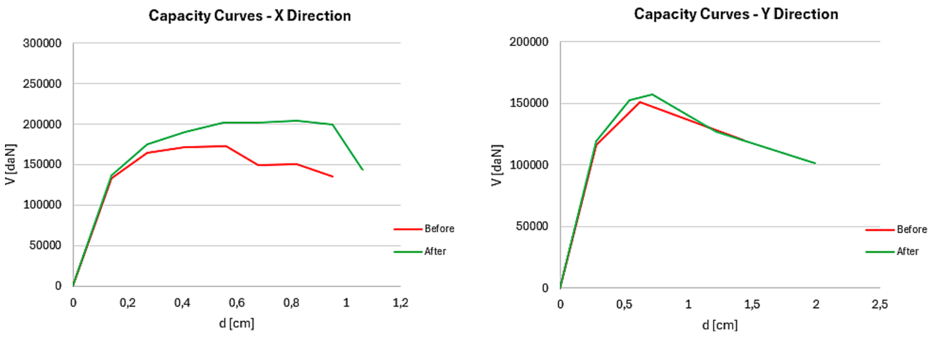
In this case, spectral displacement (S_d) was selected as the intensity measure for deriving these curves.

The probability function was evaluated using the following equation (Eq. 3):

$$P\left(d > D_{Si} | S_d\right) = \Phi \cdot \left(\frac{1}{\beta} \cdot \ln \frac{S_d}{S_{d,ds}}\right) \tag{3}$$

where:

- Φ is the standard normal cumulative distribution function;
- $S_{d,ds}$ represents the median value of the spectral displacement associated with each damage threshold;

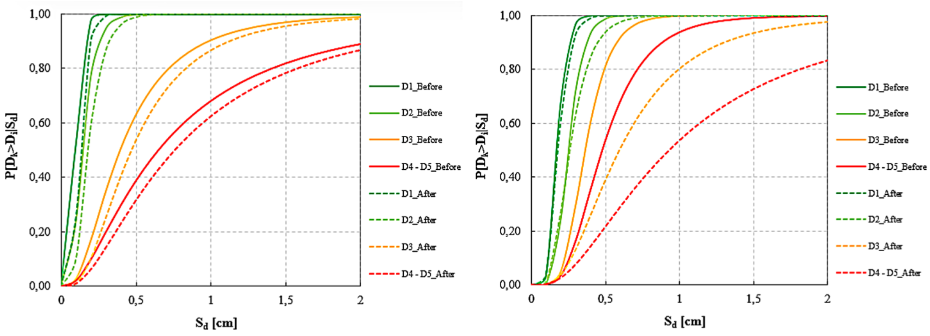


a) b)

Fig. 8 Comparison of the capacity curves before and after the installation of the seismic coat: (**a**) X – Direction; (**b**) Y - Direction

Table 3 Damage levels and corresponding standard deviation assumed for the fragility curves

Damage level	Limit displacement	Damage type	Standard deviation β_i
D1	$0{,}7d_y$	Slight	$0{,}25+0{,}07\ln(\mu)$
D2	d_y	Moderate	$0{,}20+0{,}18\ln(\mu)$
D3	$d_y+0{,}5(d_u-d_y)$	Near Collapse	$0{,}1+0{,}40\ln(\mu)$
D4–D5	d_u	Collapse	$0{,}15+0{,}5\ln(\mu)$



a) b)

Fig. 9 Fragility curves before and after the insertion of integrated coating system: (**a**) X– Direction; (**b**) Y- Direction

- β is the standard deviation of the natural logarithm of the spectral displacement, representing the uncertainty. This factor is a function of the structural ductility, μ, of the SDoF system.

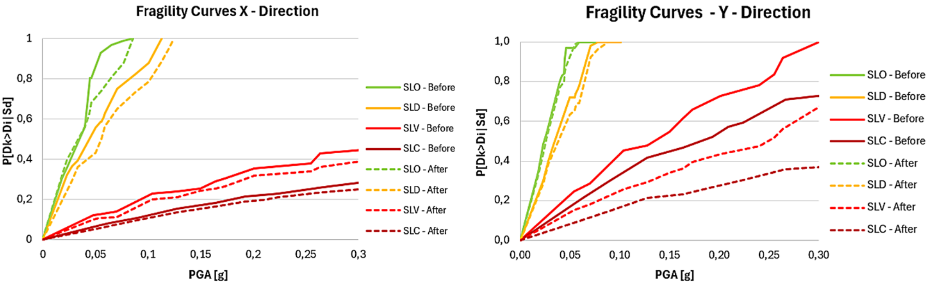
The damage thresholds used for the plotting of fragility curves were based on the study of (Lagomarsino et al. 2021), who used the yielding and ultimate displacements as reference parameters.

The damage levels and the corresponding standard deviations are indicated in Table 3.

Figure 9 depicts the comparison for each analysis directions of the fragility curves before and after the installation of the seismic coat. It is evident the positive effects provided by the presence of the integrated retrofitting technique, which ensure a significant reduction in the probability of attainment any damage levels. Particularly, along Y– direction, there is a severe decrease of the damage probability attainment at the ultimate limit states (damage level D4– D5).

In addition to the empirical fragility curves above presented, further mechanical-based fragility curves, developed on the 3Muri analysis results, were derived to facilitate a comparison among the different limit states before and after the intervention.

The methodology begins with using an elastic-plastic SDoF model as the capacity model, applying the same empirical relationships for damage thresholds outlined in Table 3, and incorporates twelve Peak Ground Acceleration (PGA) values from locations with varying seismic hazard levels as the demand model. The identification of the SDoF system is derived from the one associated with the real structure (MDoF) through the modal participation factor.



a)

b)

Fig. 10 Fragility curves: (**a**) X– Direction; (**b**) Y - Direction

The evaluation was conducted on the ADRS (Acceleration– Displacement Response Spectrum) plane in which beyond the capacity curve associated to the SDoF system, also the spectra corresponding to the twelve different PGA values were inserted. For ultimate limit states, anelastic spectra reduced by a behaviour factor q = 2.98 were considered.

The conversion from acceleration spectra to the ADRS plane was carried out using the expression provided by Eq. 4:

$$\mathrm{S_d} = \frac{T^2}{4 \cdot \pi^2} \cdot S_a \tag{4}$$

where:

- $\mathrm{S_d}$ is the spectral displacement;
- $\mathrm{S_a}$ is the spectral acceleration;
- T is the period expressed in second.

The evaluations were conducted using the N2 method on the ADRS plane, determining the ratio between demand and capacity displacements.

Particularly, the intersection between the capacity curve of the SDoF system with the different spectra determines the maximum capacity displacement of the structure.

Each chart includes four curves associated with the following four limit states:

- Operational Limit State (SLO);
- Damage Limit State (SLD);
- Life Safety Limit State (SLV);
- Collapse Limit State (SLC).

This procedure was carried out for the two main directions for the two models: before and after the installation of the seismic coat.

Figure 10 presents two graphs: the first shows the fragility curves for the X-direction, while the second illustrates them for the transverse direction.

The above figures clearly show that the fragility curves highlight a more significant reduction in probability, particularly in the case of ultimate limit states. This effect is especially pronounced along the Y-direction, where static non-linear analyses also recorded a greater percentage of seismic improvement. These results suggest that the intervention was effective in addressing vulnerabilities and enhancing the structural performance of the existing masonry clustered building.

6 Conclusions

This work evaluated the effects of applying an innovative, integrated, and lightweight retrofitting technique, consisting of a seismic-energy coating system, to a typical masonry aggregate placed in Castelpoto, a small town in the province of Benevento, Southern Italy.

Initially, the geometric and structural properties of the complex were thoroughly investigated to gain a comprehensive understanding. The case study comprises seven structural units built with various types of masonry and horizontal slabs supported by wooden or steel beams. The compound sustained significant damage from multiple seismic events, notably the 1980 Irpinia earthquake, which caused partial roof collapses and further damage to the wooden beams and masonry panels.

Static non-linear analyses were then conducted to assess the building's seismic behaviour. The results for the "as-built" configuration revealed poor seismic conditions, with low safety coefficients, indicating the need to intervene with a proper integrated seismic-energy retrofit intervention.

To address these vulnerabilities, a seismic-energy coating system, featuring extruded aluminium alloy exoskeletons coupled with thermal insulating sandwich panels, was proposed as appropriate intervention technique and introduced into the analysis. This technique stood out due to its lightweight nature, especially when compared to other similar retrofitting techniques consisting of cast-in-place reinforced concrete walls. It is easy to transport, assemble, and install, making it a cost-effective and time-efficient solution. Additionally, there are incentives available for the installation of such technologies, which further enhance its appeal as a viable retrofitting option.

The numerical investigations were repeated under the same conditions, demonstrating a substantial improvement in both safety coefficients and capacity curves, with notable increases in resistance and ductility. Specifically, the safety factor increased by 27% in the longitudinal direction (X-axis) and 46% along the transverse one (Y-axis), demonstrating a significant enhancement in the building's seismic performance.

Finally, fragility curves were plotted and compared for both the pre- and post-retrofit scenarios. In this last case, the results highlighted a significant reduction in the probability of exceeding specific damage thresholds, especially at the highest damage levels, underscoring the effectiveness of the integrated retrofit solution in enhancing both seismic resilience and energy efficiency of the inspected case study.

In conclusion, the proposed retrofitting system was demonstrated high effectiveness in improving the building's seismic response and energy efficiency. However, as this is a novel system, its full effectiveness must be validated through laboratory testing and applications to additional case studies. Once further calibrated and tested, this solution holds great potential as a cost-effective and reliable approach to improving the resilience of masonry structures exposed to seismic risk.

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Declarations

Competing interests The Authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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