

ENHANCEMENT OF SEISMIC PERFORMANCE OF HISTORICAL CLUSTERED BUILDINGS BY AN ORIGINAL SEISMIC COATING SYSTEM: A PARAMETRIC CASE STUDY IN MIRANDOLA

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Abstract

The assessment of the seismic vulnerability of unreinforced masonry buildings, particularly those in historic city centres, is crucial for preserving Europe’s architectural heritage. However, evaluating these structures, which represent a significant portion of the existing building stock, remains challenging due to limited data on their geometry and structural details, shaped by centuries of unregulated urban development. Additionally, these buildings often exhibit thermal inefficiencies due to the use of materials with low insulating properties.

This study investigates the seismic behaviour of a typical unreinforced masonry building complex placed in the historic centre of Mirandola, severely affected by the 2012 Emilia–Romagna earthquake. A parametric approach is employed to analyse the influence of key structural factors—including material type and knowledge level—on seismic performance of the masonry aggregate. Numerical simulations are conducted both before and after the implementation of an innovative seismic - energy retrofit system, which combines an aluminium alloy exoskeleton, designed for seismic reinforcement, with sandwich panels, aimed at reducing thermal losses.

The primary objective is to quantify the impact of these factors on the building's structural performance. Static non-linear analyses and a fragility assessment are carried out to identify the most influential parameters affecting the seismic behaviour of the building aggregate.

The achieved findings highlight the critical role of detailed structural knowledge, particularly regarding masonry quality and amount of available data, in predicting the building’s seismic performance. Furthermore, the proposed integrated seismic-energy solution significantly reduces vulnerability, demonstrating to be a sustainable and effective strategy for preserving the structural integrity and energy efficiency of historic masonry buildings.

Keywords: Clustered masonry buildings, Integrated Retrofit Interventions, Light Exoskeleton, Aluminium Alloy extruded profiles, Parametric Investigation, Pushover analysis.

1 INTRODUCTION

The existing building stock is primarily composed of unreinforced masonry structures, many of which are not isolated but grouped in aggregates [1, 2]. This is especially common in building complexes consisting of multiple units constructed adjacently, with varying degrees of connection effectiveness. These types of masonry compounds are typical in historic centres across Europe. They originated from unplanned urban development during the Middle Ages, often resulting from the construction of new units in the spaces between existing buildings. Within an aggregate, three distinct typologies of units can be identified: pre-existing units, growing cells, and saturation units. Pre-existing units refer to the original buildings, while growing cells are those built adjacent to these early structures. Saturation units fill the remaining gaps between the first two categories [3, 4].

As individual units within these aggregates interact dynamically, their seismic response depends on their position within the complex—whether they are at the edge, internally placed, or at a corner. This interaction is known as the aggregate effect [5, 6].

Another common characteristic of the existing building stock is that these buildings were constructed without considering horizontal forces such as seismic loads. They were designed only to support their own weight, relying on empirical construction methods without formal engineering design processes [7].

The lack of proper box behaviour—achieved through effective connections between adjacent walls and between the walls and intermediate floors—significantly increases the vulnerability of masonry structures. As demonstrated by recent seismic events across Europe, such as in Italy (2009, 2012, 2016), Turkey and Syria (2023), and Morocco (2023), this structural weakness has led to severe local and global damage, including overturning and/or flexural failures [8–10].

A further challenge in assessing the seismic vulnerability of masonry aggregates is the limited knowledge of their geometry, which is often irregular both in plan and elevation. Since individual units were built during different periods, each reflects the construction techniques of its time. Additionally, there is minimal information regarding the materials used in both vertical and horizontal elements. These materials often exhibit poor mechanical properties, as they were frequently sourced locally without strict selection criteria. Furthermore, the thermal properties of these materials can vary significantly, influencing the overall behaviour of the structure [11–13].

In addition to seismic vulnerabilities, existing buildings suffer from significant energy inefficiencies due to high heat losses. As a result, a large portion of the building stock in Italy—nearly 50%—remains classified within the two lowest energy efficiency classes (Class F and G), although this has gradually improved in recent years [14].

In response to the need to reduce emissions and energy consumption for heating and cooling, several European Union policies, including the Green Deal (2020) and Fit for 55 (2021), have promoted the development of innovative retrofitting technologies. These advancements enable a single intervention that simultaneously improves both seismic and energy performance of masonry structures [15–17].

New solutions involve external coating systems that enhance the overall structural behaviour while improving energy efficiency through the integration of thermo-insulating panels. These panels reduce heat dispersion, leading to lower energy consumption and reduced utility costs. This approach is effective for both masonry and reinforced concrete structures [18–21].

This study investigates the seismic behaviour of a typical masonry aggregate located in the historic centre of Mirandola through parametric analyses, both before and after the application

of a novel coating system composed of aluminium alloy exoskeletons and insulating panels, using a macro-elements approach.

After providing a brief description of the building complex and identifying its structural units, nonlinear analyses are conducted in two stages:

- Varying the masonry typology, including solid brick masonry, regular stone masonry, and irregular stone masonry.
- Modifying the level of knowledge from the lowest to the highest.

The aim of these analyses is to assess how the seismic response varies, identify which factors have the most significant impact, and determine which configuration produces the best results.

Each phase is followed by the development of fragility curves, a crucial tool for comparing different configurations before and after retrofitting, as well as for evaluating the effectiveness of the intervention.

The results clearly show that safety indices increase significantly, while the probability of exceeding a specific damage level decreases when the masonry is more regular and the level of knowledge is higher. Conversely, when the masonry is irregular or information about the structure and materials is limited, the aggregate performs poorly, although retrofitting provides slight improvements.

2 THE INVESTIGATED MASONRY COMPOUND

2.1 The historic centre of Mirandola and the past seismic events

Mirandola is an ancient centre placed in the district of Modena, within the Emilia-Romagna region in the northern part of Italy. The small town lies in the Po Valley and has a population of less than 25,000 inhabitants distributed over an area of approximately 138 square km.

The city still retains traces of its octagonal layout in the historic centre, dating back to its time as a fortress city during the Renaissance, as depicted in Figure 1. The historic centre also features several structures of significant architectural value.

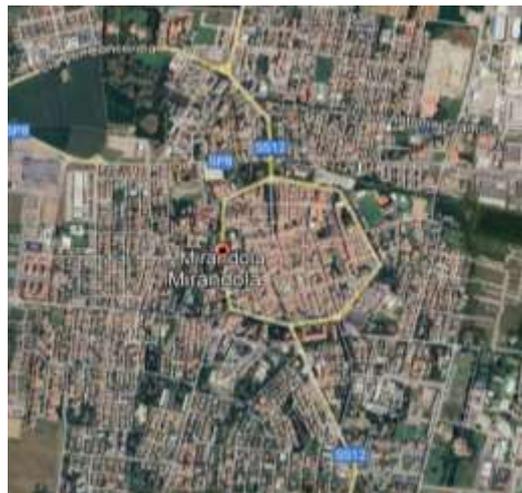


Figure 1: Top view of the city of Mirandola (Modena). Source: Google Earth, 2025.

Mirandola, like many other cities in Italy, has historical roots that may trace back to the Roman era, when the region saw the construction of roads and infrastructure. Following the fall of the Roman Empire, the area came under the control of the Lombards, a Germanic pop-

ulation that established early urban settlements. Over time, various noble families governed the city, shaping its development. The Canossa family fortified Mirandola, transforming it into a strategic military outpost, while the Pico family later contributed to its architectural and cultural growth by commissioning significant buildings such as the Duomo and the Reason Palace.

After experiencing a period of decline, the city began to recover following Italy's unification in the late 19th century. This growth continued into the 20th century when Mirandola expanded beyond the boundaries of its historic centre, giving rise to new districts and modern infrastructure.

According to the National Institute of Geophysics and Volcanology and the Civil Protection Department, the Emilia-Romagna region is classified as a medium-low seismic risk area. However, during the 2012 seismic sequence, many cities within the region experienced significant damage [22].

On May 20, 2012, the provinces of Modena, Ferrara, and Reggio Emilia were struck by a 5.9 magnitude earthquake, with its epicentre located in Finale Emilia. A second shock followed on May 29, registering a magnitude of 5.8 near Medolla [23, 24].

The seismic sequence caused severe damage to various buildings, including residential properties, churches, and factories, resulting in major economic losses. Due to widespread cracking and structural damage, thousands of residents were forced to relocate to temporary accommodation. This prompted engineers and Civil Protection teams to assess the stability of the structures and determine the necessary retrofitting interventions to ensure the safety of the building stock.

2.2 Geometric and structural features

The historic centre of Mirandola is home to several masonry compounds, most of which date back to the Middle Ages. Most of these structures consist of low-rise buildings, typically ranging from two to three stories. They feature vertical panels made of solid brick bonded with mortar, a material commonly used in the area, and intermediate floors composed of timber beams, usually supporting a single layer of planks. In some cases, the ground floor includes internal spaces covered with masonry vaults. The roof structure is also constructed from timber elements and generally follows a double-pitched configuration.

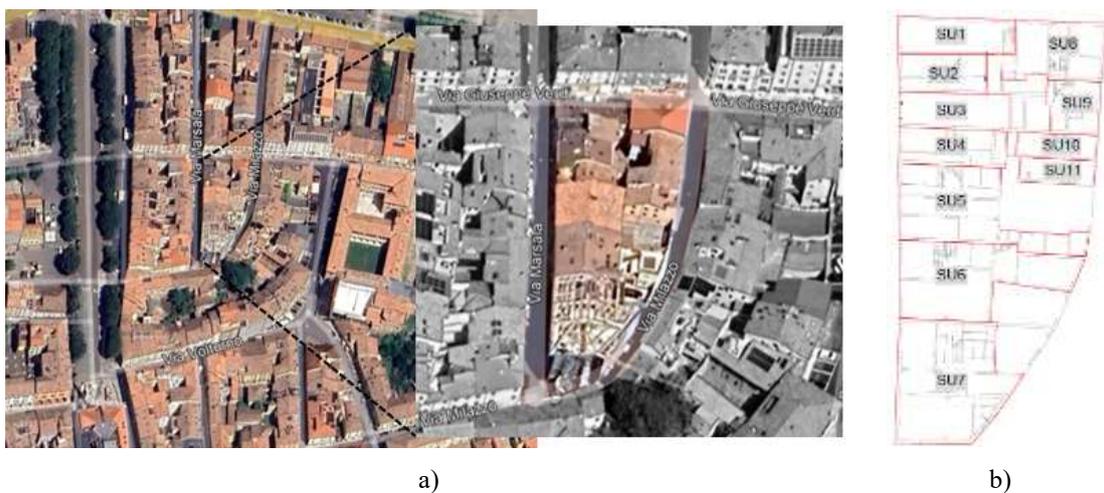


Figure 2: a) Location and geometry of the building aggregate under evaluation; b) Ground floor layout and identification of the eleven structural units.

Based on the available geometric data, the building complex illustrated in Figure 2a was chosen as a case study for parametric analyses. It is located near the town's main square, Piazza Costituente, and is bordered to the north by Garibaldi Street, to the east by Milazzo Street, and to the west by Marsala Street.

The compound has an irregular shape, consisting of eleven structural units that cover an area of approximately 1,200 square meters. These units, represented in Figure 2b, range from two to four stories above ground. The materials used in construction are typical of the region, with perimeter masonry walls made of solid bricks that vary in thickness from 25 to 50 cm.

Since Mirandola is within an area affected by the 2012 earthquake, the construction sustained severe damage, including the partial collapse of some roofs due to thrust forces and lesions near the openings. The absence of box-behavior, which is essential for ensuring a good response of masonry structures under seismic loads, led to the detachment of adjacent walls.

Several units (Nos. 3, 4, 6, 7, and 10) were retrofitted using traditional strengthening techniques, such as the insertion of metal tie rods to mitigate out-of-plane mechanisms, "scuci and cuci" interventions, and consolidating injections to enhance the resistance of the masonry panels. The remaining structural cells underwent minor repair operations [25].

3 A NOVEL INTEGRATED SEISMIC-ENERGY RETROFITTING SOLUTION

3.1 Functioning, components and main advantages

After selecting the case study aggregate, parametric analyses were conducted to assess its structural behavior before and after the retrofit intervention, which was necessary due to the damage caused by the 2012 seismic event. Instead of relying on traditional reinforcement techniques, this study proposes an innovative solution through the adoption of an integrated seismic-energy system.

The proposed retrofit technique belongs to the category of coating systems, which are external interventions designed to enhance both seismic resilience and energy efficiency. These systems represent a modern alternative to traditional consolidation methods, offering minimal invasiveness and rapid installation.

Although they are a recent introduction to the construction industry, several variations already exist. A brief overview of these variations is provided below:

- Concrete-based systems: They provide the realization of shear walls made of cast-in-place concrete between two insulating panels that serve as formwork. This is the case of Geniale Coat and Sismacoat systems [26, 27].
- Lightweight metal exoskeletons: This type of system features cold-formed steel or aluminium alloy base frames combined with thermo-insulating panels. Examples of this category include the Resisto 5.9 and Duo System seismic coats [28, 29].
- Timber-based systems: This is the case of the Betonwood system, which integrates timber structures with insulation panels [30].

Among these, the MIL15.s system, manufactured by TM Group S.r.l., was selected for this study [31]. This innovative technique utilizes aluminum alloy profiles (AW6060 – T6), which are produced through an extrusion process, followed by thermal treatment and artificial aging.

The design and verification of all components, including the connections, were carried out in accordance with the guidelines provided by Eurocode Standard 9 [32].

The system and its components are shown in Figure 3.

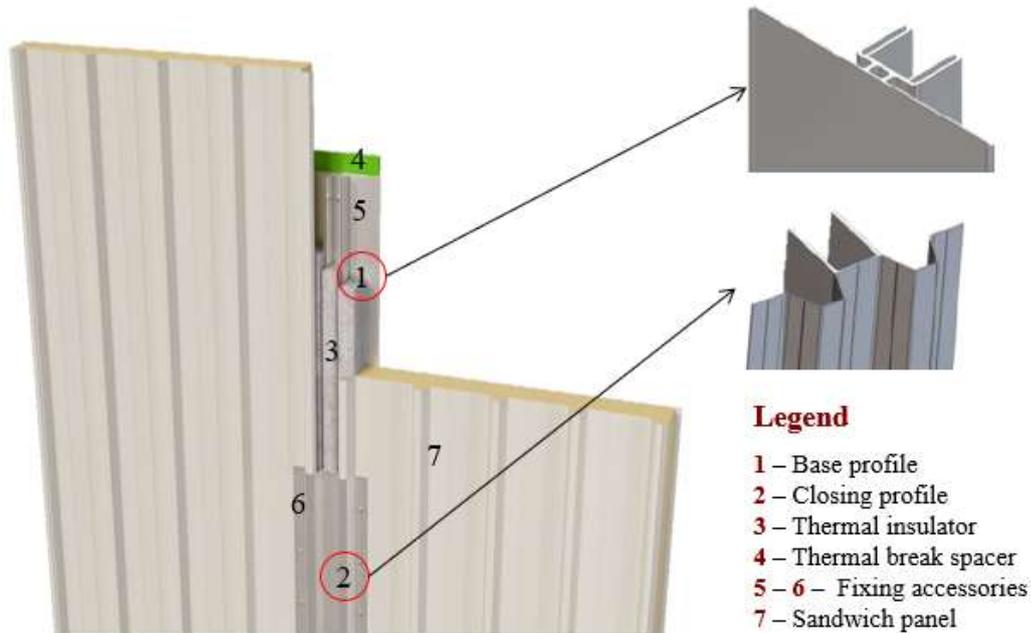


Figure 3. View of the integrated seismic-energy MIL15.s system.

The external coat system consists of several key components. First, base profiles (No. 1 in Figure 3) are attached to the perimeter structure's walls using chemical anchors (12 mm in diameter, No. 5). Next, thermal-insulating sandwich panels (No. 7) are installed by securing them between two adjacent base profiles, which are spaced approximately one meter apart. These panels feature double trapezoidal sheeting, and their internal core can be filled with various materials, including polyurethane, rock wool, or eco-friendly alternatives such as cork, hemp, or straw, depending on the desired thermal performance. Finally, closing profiles (No. 2) complete the assembly. These profiles are fixed to the external sheeting of the sandwich panels using self-drilling screws (5.5 mm in diameter).

This retrofitting solution offers multiple advantages. Firstly, it serves a dual purpose by enhancing both seismic performance and energy efficiency, enabling the building to achieve box-like behavior while simultaneously reducing thermal losses from indoor spaces. The system, constructed from aluminum alloy elements, is three times lighter than steel, ensuring it does not add extra load to the existing structure. Furthermore, aluminum's natural resistance to corrosion, without the need for special treatments, makes it an ideal material choice. Additionally, aluminum is highly sustainable, as its components can be fully recycled at the end of their lifecycle.

The system is custom-produced and is based on in-depth on-site inspections, which ensure that all components are prefabricated and only require assembly and anchoring to the building. This streamlined approach leads to significant cost and time savings. Another key benefit is that, as an external envelope system, its installation does not interfere with internal activities, and there is no need to relocate inhabitants.

The initial cost of the MIL15.s system is approximately €200 per square meter, which includes both supply and installation. While this cost is comparable to traditional reinforcement methods (such as FRP or FRCM), the MIL15.s system also provides additional thermal benefits, leading to long-term savings on heating and cooling.

4 SEISMIC BEHAVIOUR BEFORE AND AFTER CONSOLIDATION THROUGH PARAMETRIC ANALYSES

4.1 Premises

Once the geometric properties of the selected case study were determined, the next phase involved conducting parametric analyses to evaluate the influence of different factors. This type of analysis is essential for investigating how seismic vulnerability changes in a building and identifying which parameters have the most significant impact.

All mechanical characteristics of the masonry and non-linear analyses were conducted following the guidelines outlined by the Italian Technical Code and the relevant Circulars [36, 37].

As mentioned in the introduction, the analysis focused on varying key parameters:

- **Masonry Type:** The first set of analyses examined three different types of masonry. The original configuration, which consisted of solid bricks, was compared to both irregular and regular tuff masonry ones. In all cases, intermediate floors made of timber beams were considered.
- **Level of Knowledge:** The second stage involved different levels of knowledge. The base configuration included the lowest knowledge level having a confidence factor equal to 1.35. Subsequently, the other two levels were considered, increasing the confidence factor up to 1.

All the possible combinations of these parameters are summarized in Table 1. Since the analysis also considered the retrofitted state, a total of eighteen models were evaluated.

		1	2	3	4	5	6	7	8	9
Masonry type	Solid bricks	■	■	■						
	Irregular Tuff Stone				■	■	■			
	Regular Tuff Stone							■	■	■
Floor type	Timber Beams	■	■	■	■	■	■	■	■	■
Soil Type	A	■	■	■	■	■	■	■	■	■
Knowledge level	KL1	■			■			■		
	KL2		■			■			■	
	KL3			■			■			■

Table 1. Combinations of factors for parametric analyses

The macro-elements approach was employed in the definition of the model. Specifically, the 3Muri software by STA.DATA was used. This software is widely adopted by researchers due to its versatility and suitability for analysing various types of structures [39].

Figure 4 illustrates the model both before and after the application of the integrated seismic-energy coat along the perimeter masonry walls.

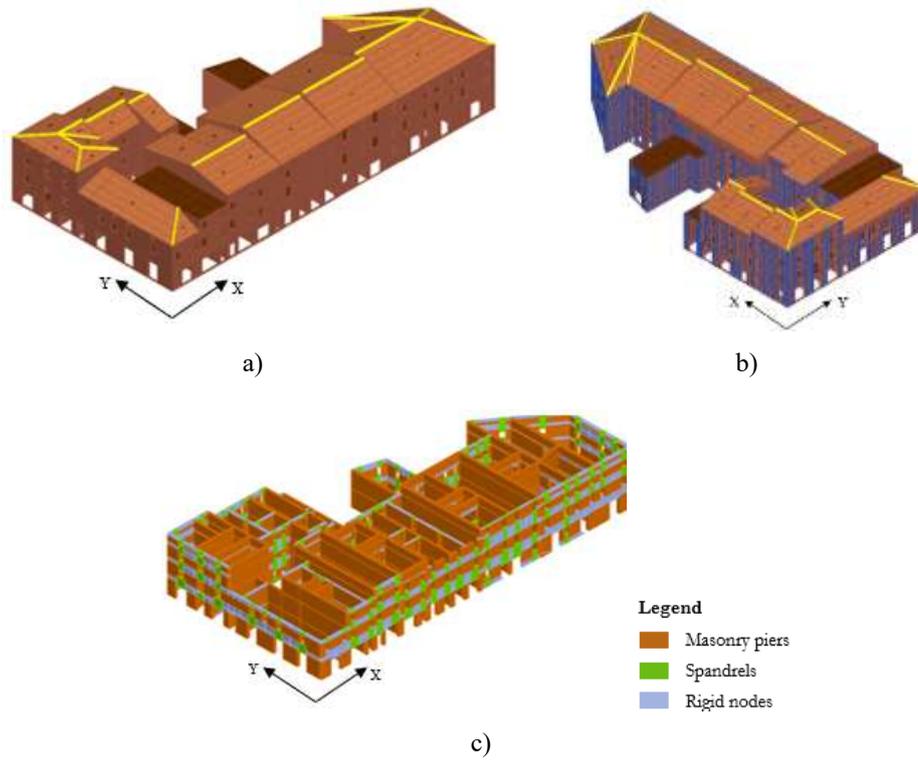


Figure 4: The case study modelling: a) Three – dimensional model before retrofit; b) Three - dimensional model after retrofit; c) Meshed model without reinforcement intervention.

The introduction of the coat was modelled by inserting vertical elements representing the aluminium alloy profiles, along with equivalent diagonal bracing to represent the sandwich panel. The vertical components are connected to the perimeter masonry walls using rigid links.

The diagonal elements are modelled with a full circular cross-section, the area of which is calculated using Eq. 1:

$$A_{diag} = K_{eq} \cdot l_{eq} / (E \cdot \cos^2 \alpha) \quad (1)$$

where:

- E is the aluminium alloy elastic modulus;
- l_{eq} is the equivalent length, equal to $b/\cos \alpha$, where b represents the frame width and α is calculated as $\arctg(h/b)$, being h the frame height.
- K_{eq} is the equivalent stiffness.

The equivalent stiffness K_{eq} of each diagonal derives from the inverse of the diaphragm shear flexibility C' .

The updated model accounts for the additional weight introduced by the exoskeletons, which remains relatively limited thanks to the lightness of the aluminium alloy material.

In both configurations, pre- and post- intervention, after creating the models and defining the mechanical properties of materials, non-linear analyses were carried out considering the two force distributions outlined by Italian Standard Code.

Static non-linear analyses were performed by monitoring the displacement of a top control node with a barycentric position. They provided the α_{SLV} coefficient, that is expressed as the ratio between the capacity peak ground acceleration and the demand one.

Each mechanical analysis is followed by a fragility study, which aims to compare the two configurations and assess the effects of both parameter variations and the innovative retrofitting technique.

4.2 The influence of different masonry types and knowledge levels

During the parametric analyses, both the masonry type and the knowledge level were varied. Starting with the original configuration, which consists of solid brick masonry, two additional types were considered: irregular and regular tuff masonry. In all cases, timber floors were assumed as intermediate decks. At the same time, the knowledge level (KL) was adjusted to examine how different levels of structural understanding influence the analysis.

The knowledge level (KL) essentially reflects the amount of information available about the structure based on investigations and tests conducted. The more data collected, the lower the uncertainty in the analysis. According to current technical standards, three knowledge levels are defined:

- KL1 (Lowest Knowledge Level): This level relies on basic information, such as a historical-critical analysis and geometric survey, with only a few material tests. Due to high uncertainty, a conservative confidence factor of 1.35 is applied.
- KL2 (Moderate Knowledge Level): At this level, more comprehensive testing is required, refining the mechanical properties of materials and slightly reducing uncertainty. The confidence factor is equal to 1.20.
- KL3 (Highest Knowledge Level): This level involves extensive investigations and material testing, leading to a clear understanding of the structure. Consequently, the confidence factor is reduced to the lowest value of 1.00.

By considering different knowledge levels and masonry types, the study evaluates how the amount of available data impacts the reliability of structural assessments and the effectiveness of retrofitting strategies.

The mechanical properties of each type of masonry, varying with knowledge level, are summarized in the following Table 2.

Masonry Type	Knowledge Level	Confidence Factor	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]
Solid bricks	KL1	1.35	2.60	1500	500	18	0.05
	KL2	1.20	3.45	1500	500	18	0.09
	KL3	1.00	4.30	1800	600	18	0.13
Irregular Tuff	KL1	1.35	1.40	1080	360	16	0.028
	KL2	1.20	1.80	1080	360	16	0.035
	KL3	1.00	2.20	1260	420	16	0.042
Regular Tuff	KL1	1.35	2.00	1410	450	16	0.04
	KL2	1.20	2.60	1410	450	16	0.06
	KL3	1.00	3.20	1620	500	16	0.08

Table 2. Mechanical properties of selected masonry types.

Table 3 presents the results of the seismic safety index for all models, both before and after the intervention.

The benefits of the integrated coating system are clearly evident when analyzing the seismic indices. In all cases, the retrofitting technique results in an increase in the seismic safety coefficient. In 60% of the cases, this increase exceeds 0.10, thereby meeting the seismic improvement requirements defined by the Italian Technical Code.

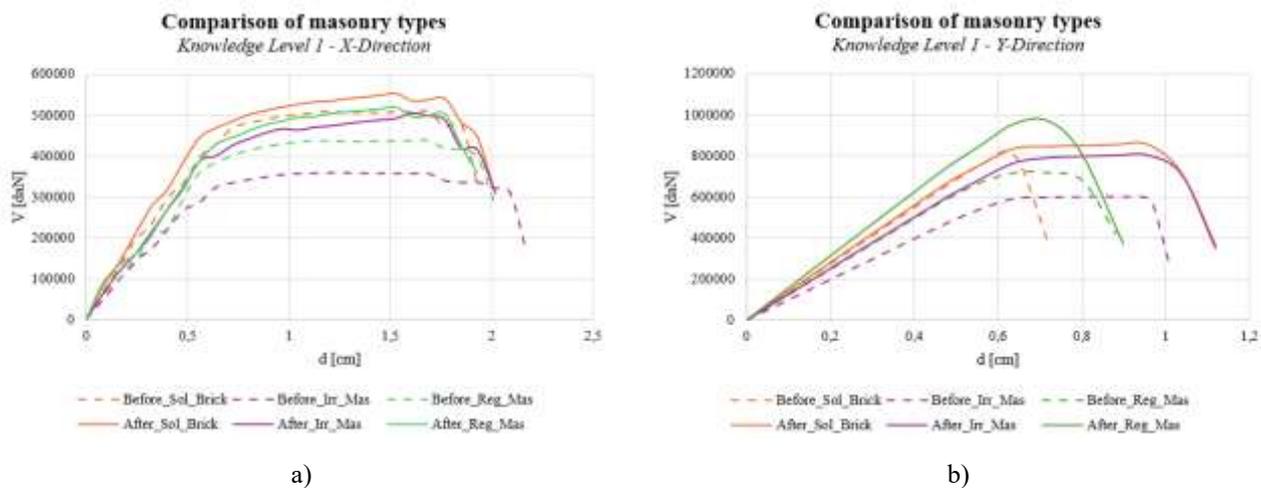
The lowest percentage of enhancement is observed in the case of irregular masonry. This can be attributed to its inherently low mechanical properties and the irregular shape of the stones, which are arranged randomly, creating weak points within the masonry texture.

Another significant aspect is the increase in the seismic safety parameter in the original state when a higher knowledge level is considered. This underscores the importance of acquiring a comprehensive understanding of the investigated building to ensure a more accurate and reliable structural assessment.

Masonry Type	Knowledge Level	Seismic Direction	Seismic Load	Before Intervention α_{SLV}	After Intervention α_{SLV}	Δ [%]
Solid bricks	KL1	+X	Uniform	0.959	1.061	11%
		-Y	Static Forces	0.494	0.646	31%
	KL2	+X	Uniform	1.159	1.312	13%
		-Y	Static Forces	0.678	0.863	27%
	KL3	+X	Uniform	1.211	1.429	8%
		-Y	Static Forces	0.838	1.058	6%
Irregular Tuff	KL1	+X	Uniform	0.893	1.055	18%
		-Y	Static Forces	0.436	0.737	69%
	KL2	+X	Uniform	0.980	1.072	9%
		-Y	Static Forces	0.708	0.773	9%
	KL3	+X	Uniform	1.017	1.109	9%
		-Y	Static Forces	0.758	0.859	13%
Regular Tuff	KL1	+X	Uniform	0.995	1.103	11%
		-Y	Static Forces	0.610	0.655	7%
	KL2	+X	Uniform	1.032	1.234	20%
		-Y	Static Forces	0.630	0.726	15%
	KL3	+X	Uniform	1.055	1.303	24%
		-Y	Static Forces	0.765	0.887	16%

Table 3. Results of non-linear static analyses considering the influence of masonry types and knowledge levels.

Figure 5 illustrates the capacity curves (Base Shear vs. Top Displacement) for both analysis directions, considering the lowest (KL1) and the highest (KL3) knowledge levels. These curves compare the three masonry typologies in their pre- and post- intervention configurations.



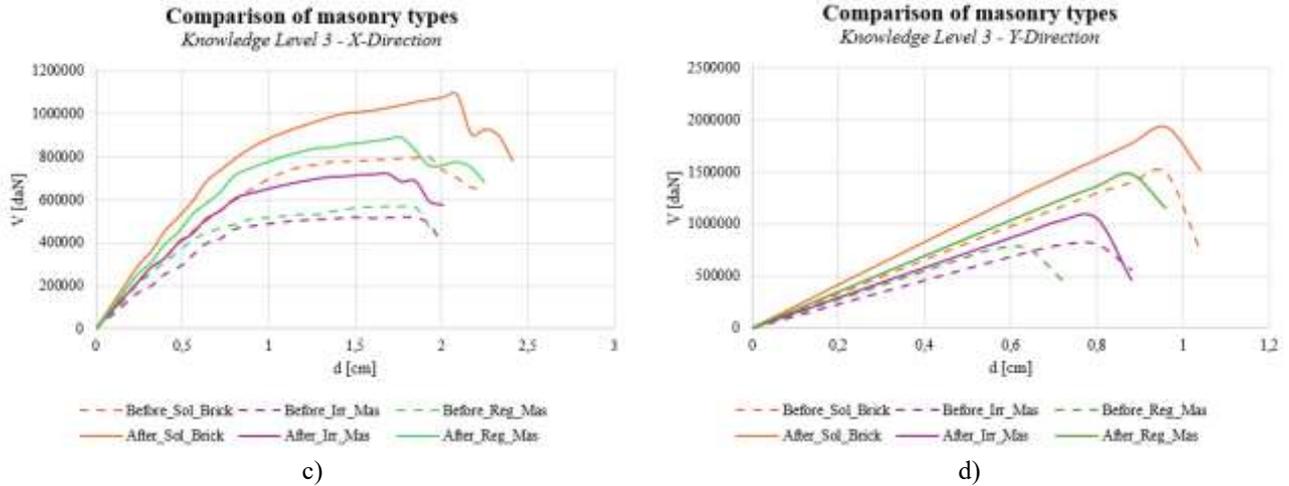


Figure 5. Comparison of capacity curves for different masonry types: a) KL1, X – Direction; b) KL1, Y- Direction; c) KL3, X – Direction; d) KL3, Y- Direction (Legend: Dotted lines = “as-built” configuration; Continuous lines = retrofitted configuration. Red: Solid brick masonry; Purple: Irregular Tuff Masonry; Green: Regular Tuff Masonry).

First and foremost, for all masonry types and knowledge levels (KL1 and KL3), the post-intervention curves indicate an increase in both resistance and stiffness, particularly along the longitudinal direction (X-axis).

The most favorable results are observed in masonry composed of solid bricks joined with mortar (curves in red). This type of masonry panel exhibits regular horizontal and vertical alignments, which contribute to a more efficient distribution of stress. Conversely, the worst performance is seen in irregular tuff masonry due to its low shear and tensile strength (curves in purple).

Based on the results of the mechanical analyses, fragility curves were developed. As is well known, these curves provide a comparative assessment of seismic risk between the original and retrofitted configurations, offering a clear visualization of the effectiveness of the proposed innovative and lightweight solution for the masonry aggregate under study. Fragility curves are widely recognized as a valuable tool for quantifying the probability of reaching or exceeding a specific damage level given a particular intensity measure [40].

In this study, spectral displacement (S_d) was selected as the intensity measure. The probability function was evaluated using the following equation (Eq. 2):

$$P(d > D_{Si}|S_d) = \Phi \cdot \left(\frac{1}{\beta} \cdot \ln \frac{S_d}{S_d} \right) \quad (2)$$

where:

- Φ is the standard normal cumulative distribution function;
- S_d represents the median value of the spectral displacement corresponding to the damage state;
- β is the standard deviation of the natural logarithm of the spectral displacement, representing the uncertainty.

The damage thresholds used for plotting of fragility curves were based on the study found in [41], where yielding and ultimate displacements as reference parameters were defined. Therefore, the corresponding damage levels and standard deviations are listed in Table 4.

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	$0,15+0,5\ln(\mu)$

Table 4. Damage thresholds and standard deviation assumed for the derivation of fragility curves.

Figure 6 compares the two configurations (pre- and post-intervention) for the best-performing masonry type (solid brick) and the worst-performing type (irregular tuff masonry) in both analysis directions for knowledge level 1.

For masonry composed of regular solid bricks, the curves in both directions indicate a significant reduction in the probability of reaching specific damage levels, with a more pronounced effect along the transverse direction.

In the case of irregular tuff masonry, the application of the seismic-energy coat provides noticeable benefits, albeit to a lesser extent than in the previous case. Nevertheless, a reduction in damage probability is observed across all damage states.

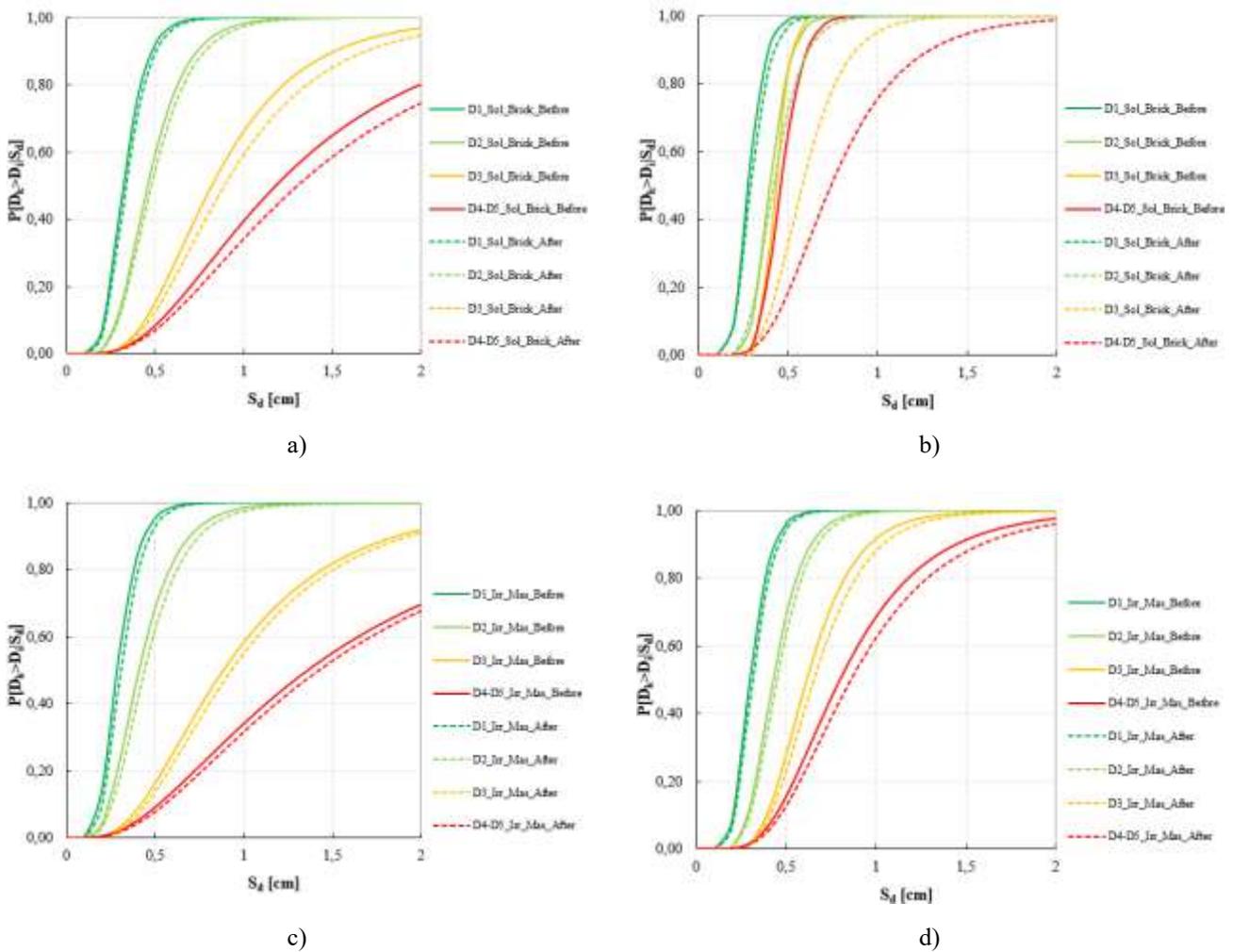


Figure 6. Comparison of fragility curves for different types of masonry: a) Solid Brick Masonry, X – Direction; b) Solid Brick Masonry, Y- Direction; c) Irregular Tuff Masonry, X – Direction; d) Irregular Tuff Masonry, Y – Direction. (Legend: Continuous lines = “as-built” configuration; Dotted lines = retrofitted configuration).

5 CONCLUSIONS

This study evaluated the seismic vulnerability of a clustered unreinforced masonry complex located in the historic center of Mirandola, within the province of Modena. The area was severely affected by the 2012 Emilia-Romagna earthquake.

Using a parametric approach, this study examined the influence of key structural factors—such as masonry type and knowledge level—on seismic response, with a particular focus on the effects of an innovative integrated seismic-energy retrofitting system.

The results indicate that both structural configuration and material properties significantly impact seismic performance. In particular, buildings with regular solid brick masonry and the highest level of knowledge (KL3) exhibit the best resistance to seismic forces, with safety index increases of up to 31%. In contrast, irregular tuff masonry remains more vulnerable, even after retrofitting, showing only modest improvements in safety indices. Meanwhile, regularly arranged tuff masonry demonstrates an intermediate performance, achieving a safety index increase of up to 24%.

The implementation of the aluminum alloy exoskeleton combined with sandwich panels has proven to be an effective retrofitting strategy, improving both seismic resistance and energy efficiency. This system enhances overall building stability, resulting in seismic safety index increases in 60% of the analyzed cases, with improvements of 10% or more. However, its effectiveness is more pronounced in configurations with higher masonry quality.

In conclusion, this study underscores the need for tailored retrofitting solutions based on a thorough understanding of each building's structural characteristics. The proposed seismic-energy coating system offers a sustainable and minimally invasive approach, providing a viable solution for improving both structural resilience and energy efficiency in historic masonry buildings. Future research should investigate the long-term durability and cost-effectiveness of such systems, as well as their applicability to a wider range of architectural typologies.

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