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Analysis of Thermal Rehabilitation and Seismic Strengthening Solutions Suitable for Heritage Structures

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Abstract: Heritage structures built in the 19th and 20th centuries in the western part of Romania are marked by the significant aesthetic influence of the Austro-Hungarian empire, with highly decorated façades facing the street and rather more simple surfaces towards the back and inner courtyard. This region is also marked by shallow earthquakes, which significantly affect the structural integrity of these buildings. Considering the current climatic context, energy efficiency regulations that also apply to the refurbishment of heritage structures, and the additional need by private owners and authorities to reduce the seismic vulnerability of these structures, it is necessary to develop integrated solutions that could improve the thermal performance of the building and strengthen its load-bearing structure, while preserving the highly valuable aesthetic features that are visible from the street. Therefore, this study is intended to investigate the viability of using different thermal rehabilitation solutions and materials that are suitable for the architectural characteristics of heritage buildings, while also integrating seismic strengthening solutions. These solutions are applied to a 19th-century building that comprises all the specific architectural and structural features found in the western part of Romania. It compares the effectiveness of using mineral-based insulation materials, cork and lime-based plasters, and aerogel–lime-based plaster applied to the inner or outer parts of the wall, depending on the solution. This solution to the problem will combine suitable wet, strengthening techniques that can be used on the inner part of the exterior walls without affecting the aesthetic value of the building. In this way, through the analysed results, this study provides valuable insights concerning potential suitable solutions that can be used to increase sustainability and reduce the seismic vulnerability of heritage masonry buildings.

Keywords: masonry heritage; thermal rehabilitation; seismic strengthening

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1. Introduction

Due to continuously changing environmental conditions and evolving energy-efficiency regulations, the thermal retrofit of historic buildings has become an important research topic in the current international context [1,2]. While the thermal rehabilitation of historic buildings with no apparent architectural value or ornamentation might be considered easy to solve, when addressing the thermal rehabilitation of valuable heritage buildings, the problem becomes rather complex since most thermal insulating materials are incompatible with preserving the building's aesthetic appearance. The decision-making process should consider the history of each building since they have significant architectural, cultural, aesthetic and social value [3]. This is why the topic is constantly being brought up by ICOMOS [4,5] and has also been approached in recent years by different researchers who hope to find solutions that can preserve the integrity of these buildings while responding to current environmental needs [6,7]. New bio-based insulating materials have been proven to have the most suitable characteristics for this task [8], offering improved thermal performance in heritage buildings while being lightweight and breathable [9] and contributing to the reduction of CO_2 emissions due to the materials used in their production [10]. In this way, rehabilitation also responds to the global agenda of actively reducing CO_2 emissions in the building sector [11].

Still, operational energy costs can be lowered by performing suitable thermal rehabilitation measures in heritage buildings, making them more attractive to various stakeholders [12]. It is, therefore, of the utmost importance to conduct multidisciplinary studies [13] that analyse how heritage buildings can be restored while also focusing on their thermal and energy performance and on strengthening their load-bearing structure so they can be used by future generations [14–16]; in this way, they can be reshaped to maximise their functionality and life expectancy [17,18].

The integrated seismic strengthening of heritage buildings is also a requirement in the current context, a process that faces the same placement problems as the thermal retrofit. Due to the architectural value of the exterior façades, in most cases, it is almost impossible to apply strengthening materials to the outer sides of the walls, and alternative solutions have to be found. Moreover, a more commonplace approach is highly recommendable since it could lead to a more cost-efficient intervention that could solve both energy efficiency problems and seismic vulnerability, while also achieving an aesthetic restoration of the building [19,20]. Despite this, studies concerning this subject are relatively few [21]. Still, studies conducted on the thermal and seismic retrofit of unreinforced masonry buildings, especially in seismic areas, highlight the fact that these solutions should focus on the inside of the building while preserving the exterior aesthetics of the building [22–25]. Conversely, if the exterior aesthetics of the building are not intrinsically valuable, various integrated systems can also be applied to the outside [26].

Thus, the current study focuses on an analysis of the feasibility of integrating both thermal and seismic retrofit solutions in unreinforced masonry buildings, using different natural-based insulation materials and strengthening techniques that could be integrated beneath this insulation material without affecting the façade of the building or also restore it. The main novelty of the study is, therefore, the proposal of a solution that is suitable for decorated heritage structures, which can be applied to a building in a single intervention without affecting the aesthetics of the building itself.

2. Materials and Methods

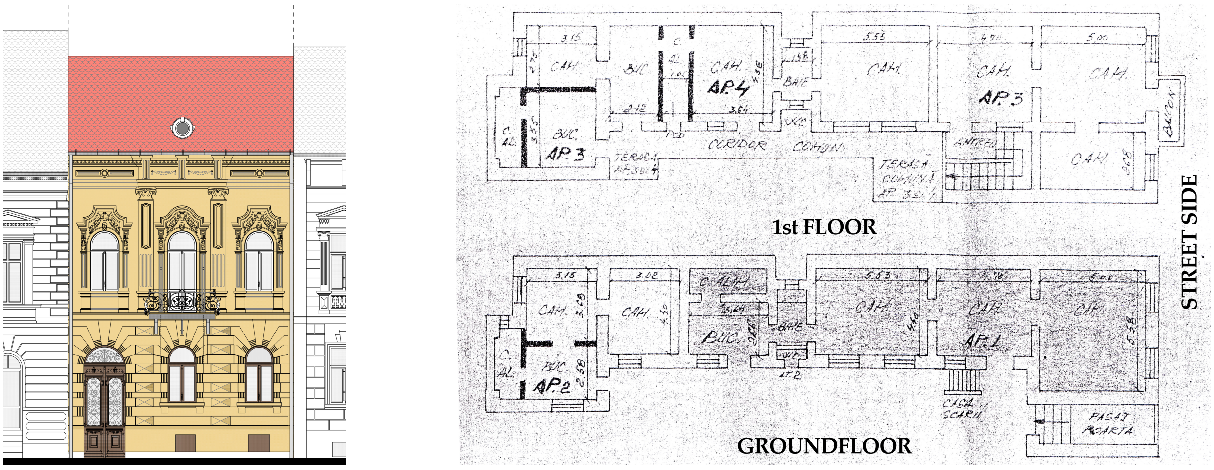
2.1. Urban Context

In order to study the effect of different thermal rehabilitation approaches and to better understand how the seismic strengthening of a characteristic heritage building in the western part of Romania might be approached, a case study from the historic part of the city of Arad was chosen that brings together all the specific architectural and aesthetic elements of the region.

The city is located close to Hungary's border, north of the Banat area, on the river Mureș. The city developed in the 17th century around a Vauban-like fortress built by the Habsburg Empire to protect the area from the Ottomans. Around the fortress, in the 18th century, different neighbourhoods started to emerge, which later merged with the fortress area, forming the current city of Arad. The neighbourhood with the most important urban value is the historical centre, which is located close to the fortress and was built in the 18th century. The historic centre still preserves most of the original urban layout and exhibits numerous valuable heritage buildings of various styles, from Baroque to Secession and Art Decó, which coexist with some Modern period buildings inserted into the urban fabric [27]. This cohesion of various architectural styles makes this historic neighbourhood highly valuable, being recognised as a class B urban heritage site, which means that preserving its appearance is important.

2.2. The Building

The object of the study is a building situated in the city of Arad, Romania. It is close to Romania's border with Hungary, north of the Banat area, on the river Mureș. Located in the city centre, it is a relatively small-sized construction that sums up the characteristics of the surrounding built environment. The main supporting structure is made of fired brick masonry and is covered in plaster. The floor over the underground level is made of brick vaulting, and the upper floors have a wooden beam structure enclosed between a wooden floor and a mortar ceiling. The accessible but unused attic space has a wooden structure covered by ceramic roof tiles, placed on steep slopes at a 33-degree angle. In total, the building has an underground level, a ground floor, an upper floor, and an attic. The building has a relatively narrow façade facing the street (Figure 1a), with apartments arranged perpendicular to the street towards the inner courtyard, with two apartments on each floor, one in the front and one in the back of the building, both accessible through an exterior walkway (Figure 1b).



(**a**) (**b**)

Figure 1. The analysed building: (**a**) street façade aesthetics; (**b**) layout of the building apartments (original building plans).

From a historical and artistic point of view, the building is relevant, especially to the rest of the street, as it is part of a continuously built building block (Figure 2). The street-side façade is decorated in the style of the time, with classical motifs used in an eclectic fashion. The decoration presents a mix of prefabricated stucco elements and thick mortar mouldings on top of the brick substrate.

(**a**) (**b**) (**c**) (**d**)

Figure 2. The analysed building: (**a**,**b**) street façade and context; (**c**) façade details and ornaments; (**d**) state of conservation of the façade.

The historical value of the city centre is recognised, the zone being a nationally protected urban area. The atmosphere of this area relies heavily on the façades of the adjacent buildings that line the urban space. Very few key buildings can be perceived as individual objects (such as the city hall, theatre building, and important high-school buildings). Most of the centre was built within a short time span and much of it shares a similar architectural language.

Internally, the studied building has a very small courtyard, nice terrazzo-finished stairs, and an internal façade that is devoid of any decoration. The upper floor is accessible using a balcony that runs along the internal courtyard façade.

2.3. Climatic and Seismic Context

The climatic context of Arad is of moderate continental type, with the influence of the sub-Mediterranean climate ensuring an average annual temperature of up to 10 °C, with generally mild winters and hot summers. According to the national methodology for calculating the energy performance of buildings (MC 001-2022), the city is part of the second climatic zone of the country, with winter temperatures of −15 °C [28].

Regarding the seismic context, the city is placed in the Banat seismic region, a region that is marked by shallow earthquakes with an epicentre placed about 15–20 km beneath the Earth's surface [29]. Due to this location, damage mainly occurs close to the epicentre [30]. According to the national seismic code (Table 1), the peak ground acceleration of the area is 0.20 g, with an upper limit of the period of the constant spectral acceleration branch (Tc) of 0.70 s [31].

Table 1. Seismic parameters according to the national seismic design code [31].

Parameter	Value
Peak ground acceleration	0.20 g
Lower limit of the period of the constant spectral acceleration branch	0.14 s
Upper limit of the period of the constant spectral acceleration branch	0.70 s
Beginning of the constant displacement response range of the spectrum	3.00 s

2.4. The Thermal Model

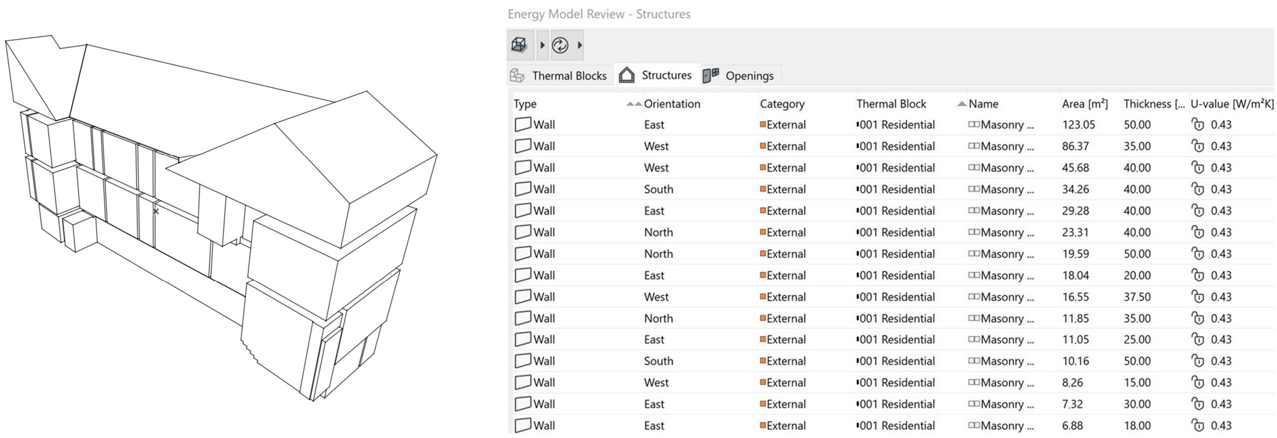
In order to be able to analyse the influence of the considered insulation materials on the thermal and energy performance of the building, two different approaches were considered. First, the building was modelled using the Archicad modelling software (version 26), according to on-site measurements. The software has an integrated energy evaluation module, which offers an easy-to-use way of performing building energy calculations for any modelled building. In order to be able to perform the energy evaluation, the software needs detailed information about the building, its surroundings, and its usage:

- A detailed model of the building had to be made, with clearly defined materials for all envelope elements. In this case, all the walls and slabs were dimensioned according to the on-site measurements and the same materials were included in the simulation.
- The geographical location criterion ultimately influences the sun's position and solar heat gain. In the case of the current study, the accurate coordinates of the analysed building were introduced to the model.
- Local climate data can be automatically imported, based on the considered location or separately uploaded based on data obtained from meteorological centres. All climatic data were automatically downloaded from the Strusoft climatic server and data about the air temperature and humidity were obtained during the performed analysis.
- The environmental setting criterion considers the immediate surroundings of the analysed building and requires data concerning wind protection and the horizontal shading of the building. Since the analysed building is placed between two other buildings and is only protected from wind to the east and west, but is also located in the city centre, partial wind protection was also considered for all the other directions.

Concerning the horizontal shading, since the street façade faces south, a low shading value for this façade was considered. Partial shadow was considered on the western side of the building, due to the existing inner courtyard, with no sunlight considered on the eastern side due to the presence of the neighbouring building.

- The operation profiles criterion focuses on how the building will be used, including the corresponding occupancy count and human heat gain, and minimum and maximum internal temperatures were set. The usage profile was set accordingly since the building is a residential building with five apartments.
- The building systems criterion offers a place where all the considered systems can be defined. In this case, since the study evaluated the actual on-site situation, only on-site gas-based heating was considered, with one unit placed in each apartment. Since no cooling or ventilation systems are currently installed in the building, they were not included in the simulation, in order to better observe the influence of the chosen insulation techniques.

In order to create the energy simulation, the software evaluates all the interior spaces and the corresponding exterior walls and openings. The interior spaces are marked with an Archicad 26 tool called "Zone", representing a spatial unit in a project that can be used to measure the area and volume of different spaces of the building. Additionally, in the tool's 3D version, they can be used as a basis for the integrated energy evaluation function (Figure 3a). Using this tool, the project's geometry can be analysed, and the software can automatically identify the envelope structures and openings. The tool also identifies the interior structures that might influence the obtained energy simulation results. Based on the materials considered for all the elements composing the building, by using the "Zones", the software can automatically determine the element's position in terms of the exterior of the building, the area of the component, its thickness, and the corresponding U-value (Figure 3b).



Type	Orientation	Category	Thermal Block	Name	Area [m²]	Thickness [...	U-value [W/m²K]
Wall	East	External	001 Residential	Masonry ...	123.05	50.00	0.43
Wall	West	External	001 Residential	Masonry ...	86.37	35.00	0.43
Wall	West	External	001 Residential	Masonry ...	45.68	40.00	0.43
Wall	South	External	001 Residential	Masonry ...	34.26	40.00	0.43
Wall	East	External	001 Residential	Masonry ...	29.28	40.00	0.43
Wall	North	External	001 Residential	Masonry ...	23.31	40.00	0.43
Wall	North	External	001 Residential	Masonry ...	19.59	50.00	0.43
Wall	East	External	001 Residential	Masonry ...	18.04	20.00	0.43
Wall	West	External	001 Residential	Masonry ...	16.55	37.50	0.43
Wall	North	External	001 Residential	Masonry ...	11.85	35.00	0.43
Wall	East	External	001 Residential	Masonry ...	11.05	25.00	0.43
Wall	South	External	001 Residential	Masonry ...	10.16	50.00	0.43
Wall	West	External	001 Residential	Masonry ...	8.26	15.00	0.43
Wall	East	External	001 Residential	Masonry ...	7.32	30.00	0.43
Wall	East	External	001 Residential	Masonry ...	6.88	18.00	0.43

(**a**) (**b**)

Figure 3. Archicad energy evaluation model: (**a**) energy evaluation model—3D display of the created Zones of the project, with the exterior envelope hidden; (**b**) energy evaluation model review, showing information about the corresponding U-value of each envelope material on the outside of the building.

The results offered by the analysis range from an overview of the building geometry data to heat transfer coefficients for all exterior constructions, with specific annual energy consumption values and CO_2 emissions (Figure 4), results that can be compared in order to understand the effect of various insulation materials in the preliminary phases of a thermal retrofit project.

Energy Performance Evaluation
Residential building Arad

Key Values

General Project Data		
Project Name:	Residential Arad	
City Location:		
Latitude:	46° 10' 14" N	
Longitude:	21° 18' 57" E	
Altitude:		
Climate Data Source:	Strusoft server	
Evaluation Date:	10.03.2024 14:55	
Building Geometry Data		
Gross Floor Area:	**711.79**	m²
Treated Floor Area:	**592.37**	m²
External Envelope Area:	**1046.21**	m²
Ventilated Volume:	**1833.54**	m³
Glazing Ratio:	**3**	%
Building Shell Performance Data		
Infiltration at 50Pa:	**2.17**	ACH

Heat Transfer Coefficients	U value	[W/m²K]
Building Shell Average:	**0.65**	
Floors:	**0.15 - 0.19**	
External:	**0.15 - 1.71**	
Underground:	**0.41 - 1.71**	
Openings:	**0.78 - 1.59**	
Specific Annual Values		
Net Heating Energy:	**32.06**	kWh/m²a
Net Cooling Energy:	**0.00**	kWh/m²a
Total Net Energy:	**32.06**	kWh/m²a
Energy Consumption:	**100.47**	kWh/m²a
Fuel Consumption:	**100.47**	kWh/m²a
Primary Energy:	**116.25**	kWh/m²a
Fuel Cost:	--	EUR/m²a
CO_2 Emission:	**21.70**	kg/m²a
Degree Days		
Heating (HDD):	**2989.68**	
Cooling (CDD):	**2051.31**	

Figure 4. Energy performance evaluation report, showing an example of some of the data that can be obtained using Archicad.

Secondly, the Ubakus website was used to better understand the heat transfer coefficient of each thermal insulation solution. This website is an easy-to-use tool with an extensive database of building materials containing all relevant technical data from different manufacturers, which can be used to determine the U-value of each construction element, heat loss, and possible moisture problems, and perform a preliminary LCA (life cycle assessment) analysis. For the LCA, the website requires information about existing and new layers of the proposed refurbishment, cost of heat generation and cost of the considered rehabilitation measure in order to determine the heating costs concerning refurbished exterior surface area, reduction of CO_2 emissions due to heating demand reduction and savings of non-renewable primary energy. It also offers, based on the decrease in heating cost, a financial amortisation period for the investment, becoming, in this way, a helpful platform for choosing the most suitable solution and convincing owners about the importance of refurbishment.

For the thermal modelling of the building, solid brick masonry was considered for the walls of the whole building, with a thermal conductivity (λ) of 0.96 W/mK. For all the other composing elements of the building envelope (slabs and openings), since their thermal performance can be easily improved, the maximal heat transfer coefficient according to the Romanian technical regulations concerning the "Methodology for calculating the energy performance of buildings, MC 001-2022" was used. Therefore, a recommended target thermal transmittance of 0.19 W/m^{2}K was considered for the slab above the underground level. In comparison, a U-value of 0.15 W/m^{2}K for new buildings was considered for the slab located below the attic. Since the refurbishment also focused on the façade, the windows were replaced with double-glazed windows in the model, with a window heat transfer coefficient of 1.11 W/m^{2}K.

In order to perform the analysis and understand the influence of different thermal rehabilitation approaches, various thermal insulation materials were applied to the exterior walls that were considered suitable for the thermal retrofit of a heritage building. Considering this element, three different materials (Table 2) of various thicknesses were taken into consideration:

- A mineral-based insulating foamed board material—an eco-friendly solution that can be used in refurbishment projects and is composed of sand, lime, cement, and water. Due to its composition, the insulating material is lightweight, does not introduce additional loads to the building structure, and is permeable to vapours, an important characteristic when dealing with heritage refurbishment and insulation being placed on the inner side of walls.
- Cork and lime-based insulating plaster is also an eco-friendly material made of natural lime, pumice stone, and cork, a breathable and porous material that is suitable for the

thermal retrofit of heritage buildings. Since it is a plaster, it can be applied in layers of 20 mm each (up to 40 mm); it is a suitable material for the interior thermal insulation of the walls but can also be applied on the outside as part of the aesthetic restoration of the façade.

- Aerogel–lime high-performance insulating plaster is also a lime-based thermal plaster that also includes aerogel, a lightweight material forming air pockets in the plaster. It becomes, therefore, highly porous, having good thermal insulating properties while also being permeable to vapours. Similar to cork and lime-based plaster, this material is also suitable for use on both sides of exterior walls.

Table 2. Considered materials for the thermal rehabilitation of a historic building.

Material	λ (W/(m·K))	Nominal Thickness	Approx. Cost/m^2 (EUR)
Mineral-based insulating boards	0.042	20–300 mm	8 (50 mm)
Cork and lime-based insulating plaster	0.075	20 mm/coating Max 40 mm	20 (20 mm) 40 (40 mm)
Aerogel–lime high-performance insulating plaster	0.028	Max 80 mm	90 (20 mm) 230 (50 mm)

Therefore, the following scenarios were taken into consideration (Table 3):

- Reference scenario, comprising the existing building with no thermal rehabilitation and a realistic usage scenario. Currently, the building is used as a residential building composed of 5 apartments, with 2 apartments on the first floor and an additional 3 on the second floor. The underground and attic spaces are currently unheated and serve as storage areas, especially the underground ones.
- Scenario 1 considers the architectural value of the building and the importance of the details and ornaments used for the façade facing the street. In the first scenario, an exclusively interior rehabilitation was considered, using mineral-based insulating boards that are suitable for an interior thermal retrofit. The only disadvantage of this solution is the slight (50 mm) reduction of the area available for the interior spaces.
- Scenario 2—Similar to scenario 1, this scenario also focuses on preserving the architectural value of the façade and proposes an exclusively interior rehabilitation using a cork and lime-based insulating plaster. Due to the maximal recommended thickness of 40 mm, this solution would affect the area of the interior space less.
- Scenario 3—Since a rehabilitation of the façade facing the street is also necessary, the third scenario considers the use of a cork and lime-based insulating plaster on both the exterior and the interior, thereby increasing the total insulation thickness to 60 mm (40 mm on the inside, where no decoration is present, and an additional 20 mm on the outside, meant to also restore the historic façade).
- Scenario 4—Similar to scenario 2, this scenario also proposes an exclusively interior rehabilitation method using an aerogel high-performance insulating plaster. Although this type of insulating plaster can be used with a maximum recommended thickness of up to 80 mm, in order not to reduce the area of the interior space, a thickness of 50 mm was considered.
- Scenario 5—Similar to scenario 3, since the rehabilitation of the façade facing the street is also necessary, the fifth scenario considers the use of aerogel high-performance insulating plaster on both the exterior and the interior walls, thereby increasing the total insulation thickness to 70 mm (50 mm on the inside, where no decoration is present, and an additional 20 mm on the outside, meant to also restore the historic façade).
- Scenario 6—This scenario proposes a combination of the previously considered scenarios, with 50 mm of mineral-based insulating material placed on the interior side of the wall and 20 mm of cork and lime-based insulating plaster on the outside to complete the aesthetic restoration of the façade.

- Scenario 7—Similar to scenario 6, this scenario proposes a combination of the previously considered scenarios, with 50 mm of mineral-based insulating boards placed on the interior side of the wall and 20 mm of aerogel–lime high-performance insulating plaster on the outside to complete the aesthetic restoration of the façade.

Table 3. The analysed thermal rehabilitation scenarios.

Scenario	Interior Insulation Material	Exterior Insulation Material
0	-	-
1	Mineral-based insulating board material	-
2	-	Cork and lime-based insulating plaster
3	Cork and lime-based insulating plaster	Cork and lime-based insulating plaster
4	-	Aerogel–lime high-performance insulating plaster
5	Aerogel–lime high-performance insulating plaster	Aerogel–lime high-performance insulating plaster
6	Mineral-based insulating board material	Cork and lime-based insulating plaster
7	Mineral-based insulating board material	Aerogel–lime high-performance insulating plaster

2.5. Seismic Strengthening

During 2022 and 2023, a series of tests were conducted on masonry specimens similar to those found in typical 19th-century buildings. The samples were made according to comprehensive studies performed on 105 historic buildings from the region, which addressed the building materials and construction technologies used in 19th-century buildings. According to the study, the investigated buildings were made of burnt clay bricks and lime mortar with perimeter walls decreasing from 90 cm in the basement area to 45 cm in the case of the floors above ground. All the walls are of English bond [32].

The test samples were built and tested according to ASTM E519/E519M [33], with 15 indications. The materials used were historic brick units from a demolition site with 290 × 140 × 65 (L × W × H) dimensions. The mortar was lime–sand with a similar composition to the historic mortar. The samples used an English bond of 1.5 units (450 mm) in thickness, reaching an in-plane dimension of approximately 1200 × 1200 mm (Figure 5).

The focus of the test was to find out how strengthening performed on only 1 side would fare compared to a typical 2-sided strengthening method.

Three sets of samples were produced. The first was not strengthened and served as a baseline. The second set comprised samples strengthened with composite material on both sides. It consisted of a ~10 mm contemporary lime-based special mortar embedded with 2 perpendicular layers of unidirectional steel fibre sheets (Table 4). The third set was similarly strengthened on only 1 side but used the same section of fibres as the previous set (Figure 6).

Table 4. Considered materials for seismic strengthening of the historic building.

Material	Nominal Thickness	Approx. Cost/m^2 (EUR)
Lime-based mortar suitable for URM strengthening	10 mm	5.6 (10 mm)
Unidirectional steel fibre sheets	0.17 mm	34

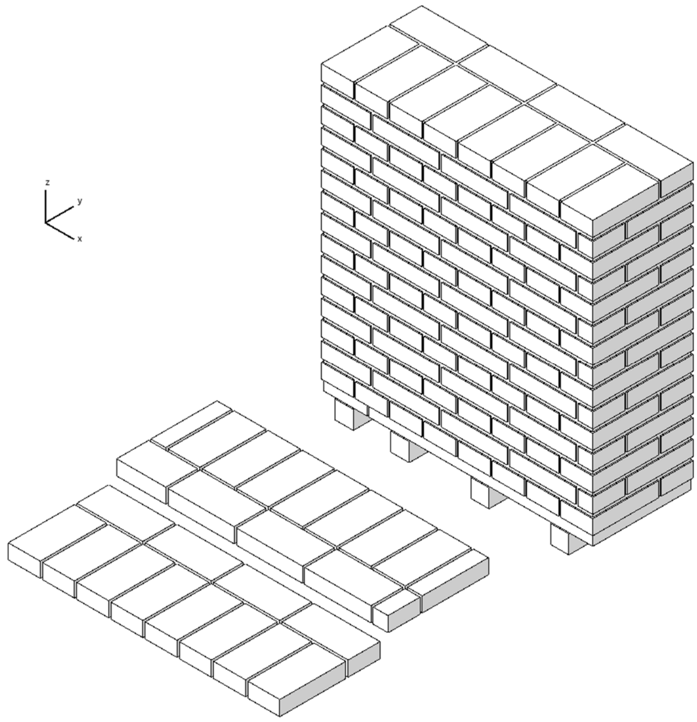


Figure 5. Laboratory testing sample with the corresponding English bond.

Figure 6. Laboratory testing—one-sided reinforcement of the sample.

3. Results

3.1. Thermal Refurbishment Results

In order to understand the effect of the different thermal refurbishment scenarios, all the data obtained from the thermal modelling process was analysed and compared.

3.1.1. Thermal Transmittance and Condensation

First, the preliminary data obtained from Ubakus were analysed in order to see the influence of each insulation solution on the thermal transmittance of the wall (Table 5). According to the updated "Methodology for calculating the energy performance of buildings", MC 001-2022 [28], the recommended maximal U-values of the walls should be 0.33 W/m^{2}K for retrofitted residential buildings. With an exterior wall thickness of 40 cm of historic solid brick masonry, the current building has a U-value of 1.705 W/m^{2}K, well above the recommended value. When applying the different thermal insulation materials, it was observed that the mineral-based insulating boards reduced the U-value by 69% to 0.531 W/m^{2}K when only 50 mm of insulating material was placed on the inner side of the wall. Since the insulating material was placed on the inside, an increase in the condensation amount was observed on the inner side of the masonry wall of 0.62 kg/m^2, with a corresponding drying time of 77 days, which allows the structure to dry out during summer.

Table 5. Exterior wall U-value and the corresponding heat capacity, condensation, and drying time for the considered scenarios.

Scenario	U-Value (W/m^{2}K)	Heat Capacity (kJ/m^{2}K)	Condensation (kg/m^2)	Drying Time (Days)
0	1.705	800	0.20	10
1	0.531	730	0.62	77
2	0.835	736	0.36	41
3	0.683	744	0.09	12
4	0.429	731	0.68	92
5	0.334	735	0.39	54
6	0.471	734	0.46	63
7	0.397	730	0.25	35

For the scenarios involving cork and lime-based insulating plaster, it was observed that compared to the reference building, the U-value would decrease by 51% if the plaster is only used on the inside (40 mm of insulating plaster) and by 59% if insulation is considered on both the inside and outside (40 + 20 mm of insulating plaster). In both cases, the condensation amount and drying time do not exceed the allowable amount, and the structure would still dry out in summer.

One-sided thermal refurbishment with 50 mm of aerogel–lime high-performance insulating plaster decreases the U-value to 0.429, representing a 74% reduction that provides one of the best insulation solutions. From a condensation point of view, however, this solution is the only one that slightly exceeds the permitted drying time of 90 days, which could lead to permanent moisture in the structure, even after a dry season. When using the same material on both sides of a wall (50 + 20 mm), the only solution complying with the national norm concerning the refurbishment of historic buildings was obtained. Even from a moisture content point of view, the condensation amount does not exceed the allowable limit, and the structure would still dry out in summer.

Finally, a combination of the considered materials was analysed. When combining 50 mm of mineral-based insulating board material placed on the inside and cork and lime-based insulating plaster on the outside of the walls, the U-value decreased by 72%, leading to a condensation amount of 0.46 kg/m^2, an amount that causes no moisture problems for the refurbished building. The mineral-based insulating boards and aerogel–lime high-performance insulating plaster scenario also almost reaches the recommended maximal U-value according to the national norm, at 0.397 W/m^{2}K, and also presents no problems concerning the condensation amount, with only 35 days of drying time.

The U-value comparison (Figure 7) shows that scenarios 4, 5, and 7 are closest to the recommended maximal U-values of the walls, at 0.33 W/m^{2}K for retrofitted residential buildings. Still, a significant improvement can also be observed in all the other scenarios, with U-value reductions from 51 to 80%.

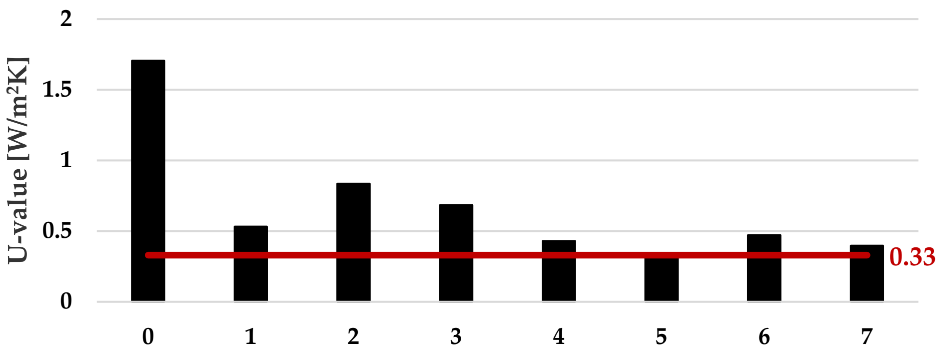


Figure 7. Resulting U-value (W/m^{2}K) for each scenario.

3.1.2. Heating Energy

Subsequently, the results obtained from the Archicad 26 numerical model were analysed, focusing on the annual heat energy demand and the heating CO_2 emission reduction obtained from the suggested thermal refurbishments (Table 6). Compared to the annual heat energy demands of the existing building and its CO_2 emissions, all the scenarios present a clear reduction in both sets of analysed values. In the case of the annual heat energy demands, the lowest reduction of 29% was observed in the case of the one-sided cork and lime-based insulating plaster scenario and showed a maximal decrease of 46% in the case of the double-sided aerogel–lime high-performance insulating plaster scenario, which also showed the lowest U-value.

Table 6. Heating energy demand and heating CO_2 emission reduction, based on a heated floor area.

Scenario	Heat Energy Annual Demand Reduction (%)	CO_2 Emission Reduction (%)
1	−42.60	−12.40
2	−29.00	−18.20
3	−34.60	−14.70
4	−43.20	−18.40
5	−46.30	−19.70
6	−41.90	−17.80
7	−44.30	−18.80

The same pattern was observed when analysing the CO_2 emission reduction, with values decreasing by between 12 and 20%.

3.1.3. Energetic, CO_2, and Financial Amortization

Since the refurbishment will improve the U-values in all the considered scenarios from 1.7 W/m²K to 0.33–0.83 W/m²K, and the annual heating energy demands are consequently lower, this would result in an annual heating energy saving of approximately 54 to 91 kWh/m². Significant savings were also observed in the model for the equivalent CO_2 emissions of the refurbishment since the materials used are all eco-friendly, according to the provided manufacturer's technical data sheets, with low CO_2 emissions (Table 7).

Based on the obtained annual heat energy savings, the corresponding heating cost, and the cost of the refurbishment/m^2, the platform can determine the energy, CO_2, and financial amortisation of the refurbishment (Table 8, Figure 8).

- The energetic amortisation time refers to the energy required for the production of the considered refurbishment materials with regard to the annual heat energy savings. Since all the materials used are eco-friendly, the obtained amortisation time is under 0.3 years for every scenario.
- The CO_2 amortisation time refers to the CO_2 emissions generated by the used materials with regard to the CO_2 emissions savings generated by the heating of the building after

the refurbishment. The shortest amortisation period was observed for the mineral-based insulating board and the cork and lime-based insulating plaster scenarios, where a balance was reached after 0.2–0.3 years. The highest amortisation period was observed for aerogel–lime high-performance insulating plaster, at up to 0.8 years.

- The financial amortisation assessment evaluates the renovation costs with regard to the heating cost savings/m^2 after the refurbishment. Since the aerogel–lime high-performance insulating plaster is rather expensive, with a mean cost of EUR 45/m^2/10 mm, the expenses for the refurbishment would be balanced after 17.6–19.8 years, or 10.8 years in the case of the mineral-based insulating boards and aerogel–lime high-performance insulating plaster. The scenarios involving mineral-based insulating boards have the lowest financial amortisation period, which is 1.6 years, in the case of the first scenario.

Table 7. Annual energy savings, cost reduction, and CO_2 savings based on U-value improvement.

Scenario	Annual Heat Energy Saving (kWh/m^2)	Annual Heating Cost Reduction (EUR/m^2)	CO_2 Savings (eq. kg CO_2/m^2)
1	76	4.60	16.00
2	54	3.20	11.30
3	65	3.90	13.70
4	84	5.00	17.60
5	91	5.40	19.00
6	81	4.90	17.00
7	86	5.20	18.10

Table 8. Energetic, CO_2 and financial amortisation of the refurbishment.

Scenario	Energetic Amortization (Years)	CO_2 Amortisation (Years)	Financial Amortisation (Years)
1	0.2	0.2	1.6
2	0.1	0.3	8.2
3	0.1	0.3	9.4
4	0.2	0.6	17.6
5	0.3	0.8	19.8
6	0.2	0.3	4.6
7	0.2	0.5	10.8

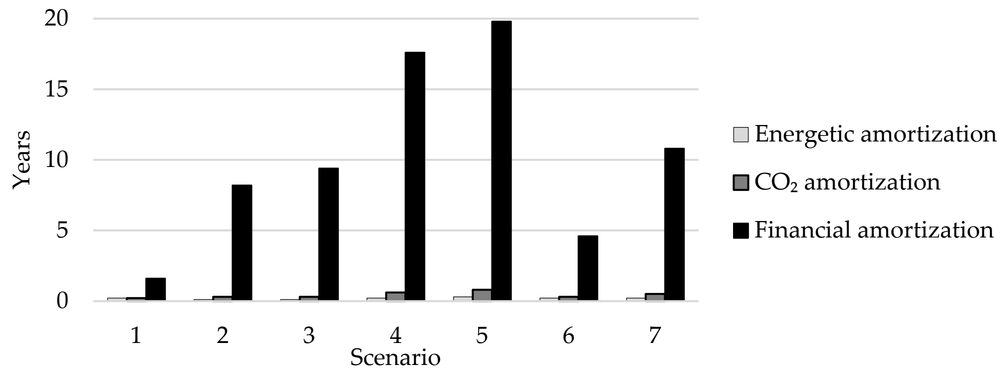


Figure 8. Energetic, CO_2 and financial amortisation of the refurbishment.

3.2. Seismic Strengthening Results

When analysing the results obtained from the laboratory tests, it was observed that even if double-sided strengthening can increase the loading capacity of the wall three-fold on the unreinforced wall (284.87 kN vs. 79.75 kN), strengthening on only one side can be completed without affecting the decorated side and almost doubles the loading capacity (maximum load 154.50 kN), which is a significant increase. Moreover, the modelled failure of the wall shows much more ductility with strengthening on one side, versus a pure brittle failure for the unreinforced sample.

The stress–strain responses of the samples can be seen in the chart below (Figure 9).

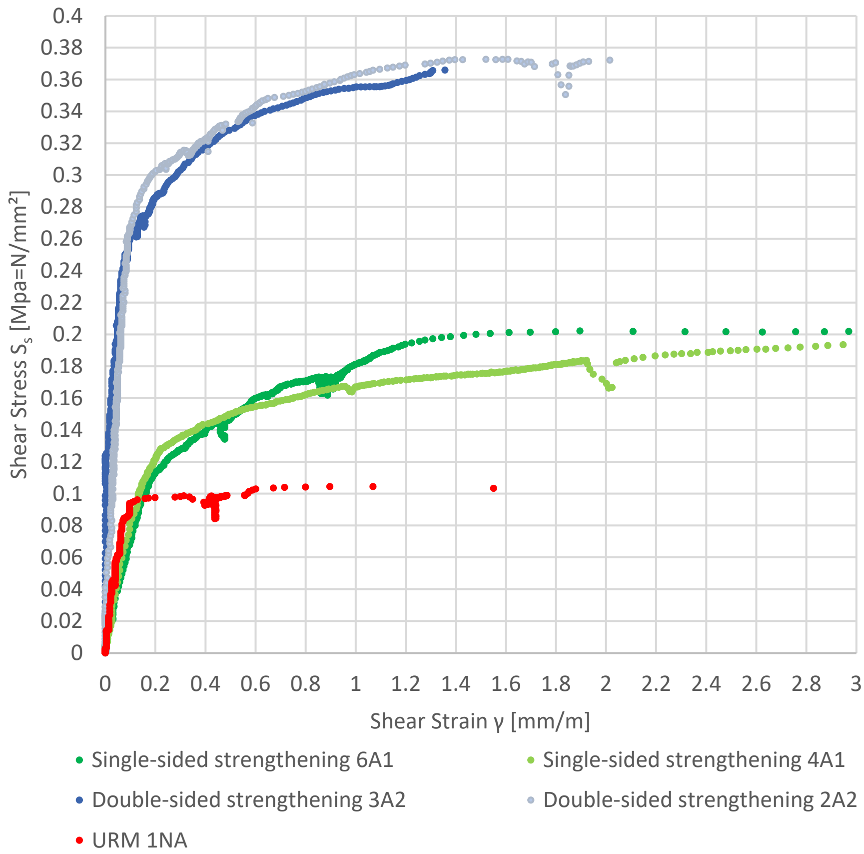


Figure 9. Comparison of the shear strain γ (X) vs. shear stress Ss (Y) responses of the tested unstrengthened and strengthened masonry samples.

4. Discussion

The current study offers essential results in two different directions, with both regarding the protection of heritage buildings from a structural and aesthetic point of view. These viewpoints can be merged in order to ensure a more cost-efficient approach, which can ultimately be used to extend a building's lifetime and increase the comfort of its inhabitants and also their safety in seismic-prone areas.

First, the study shows that there is a series of materials that are currently available on the market that can be used to refurbish heritage buildings, which use natural-based materials and ensure the high breathability of the exterior envelope. Despite offering similar results concerning the obtained thermal transmittance and a reduction in the heating costs, the investment amortisation proves to be very different according to the costs of the materials used in the refurbishment. This factor might be highly influential in the decision-making process.

Secondly, the study shows that seismic strengthening solutions can also be applied with consideration for the aesthetic value of a building, forming a thin layer in comparison to the total wall thickness (10 mm vs. 400 mm) in a matrix that is also lime-based, with μ values of between 15 and 35. This is compatible with the mortars and renders that are used in historic walls and are suitable as a base for any thermal upgrade materials, which can easily be applied on top of it.

This study shows that integrating these two solutions can potentially improve the structural, thermal, and aesthetic performance of an existing building without contributing to an increase in its mass, also leading to a nominal reduction in the usable interior space.

Since the treatments are applied on the inner side of the exterior walls, external decorations can be preserved and interventions can be made while also rehabilitating the inside of the buildings, which, in many cases, is also decayed and in need of intervention. More than this, all the considered retrofit solutions use eco-friendly materials, thus generating low CO_2 emissions during the intervention while also reducing CO_2 emissions due to the reduction in heating demand during the lifetime of the building after the retrofit. Additionally, the integrated seismic retrofit of the building also reduces the need for additional structural interventions in the future, preventing additional CO_2 emissions caused by the maintenance of the building.

5. Conclusions

This study presents an original approach to applying integrated thermal and seismic retrofit solutions that are suitable for heritage structures presenting highly valuable architectural elements on the outer side of the exterior façades.

The solution's novelty lies first in integrating reinforcement between the load-bearing structure and the insulation material. Due to the reduced thickness of the seismic strengthening layer, little usable space is lost inside the building while significantly increasing the structure's load-bearing capacity, according to laboratory tests. Secondly, the main novelty lies in the protection of the main decorative elements placed on the exterior side of the façades through the placement of the main thermal and seismic retrofit solution on the inner side of the exterior wall, while keeping an eye on the condensation amount. Still, insulating plaster can also be used on the outside of the building in order to restore the façade.

The general effectiveness of the solutions considered was highlighted by the presented heat energy and CO_2 savings and annual heating cost reductions, together with the results obtained during the laboratory tests regarding the in-plane behaviour of strengthened masonry structures. Therefore, the study offers valuable information for historic building owners, local authorities thinking about heritage refurbishment, and other researchers involved in protecting heritage structures.

This study represents a first step concerning the integrated thermal and seismic retrofit of characteristic heritage buildings in Romania and in most parts of Europe, where the historic building stock is highly diverse and buildings must also be adapted to current climatic conditions. Therefore, studies are still necessary to understand how the results obtained during these laboratory tests can be applied to a whole building and its seismic behaviour before and after the retrofit.

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