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AN INNOVATIVE LIGHTWEIGHT INTEGRATED SEISMIC – ENERGY COATING SYSTEM FOR THE RETROFIT OF A MASONRY CLUSTERED BUILDING IN TIMIŞOARA CITY (ROMANIA)

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Summary. Unreinforced masonry buildings represent a large portion of the building stock in most historical centres of European countries. In many cases, these constructions are not isolated, but grouped in clustered buildings made up of multiple adjacent structural units erected in continuity one to each other. Moreover, these constructions were realized without any seismic criteria and, nowadays, their requalification is an urgent need from both structural and energy points of view. In this paper, the vulnerability assessment of a masonry aggregate placed in Timişoara city (Romania) is investigated. Firstly, after collecting the main properties of the structure, non – linear analyses were performed obtaining the capacity curves.

Subsequently, since the behaviour appeared inadequate to withstand seismic actions, a retrofit intervention was hypothesized. The choice was directed towards the use of lightweight metal exoskeletons arranged along the external facades of the aggregate, so to create a continuous coating. This solution simultaneously allowed for the improvement of both seismic and energy performances of the building, as the profiles are coupled with insulating panels.

Finally, after the envelope system was dimensioned, its effectiveness was demonstrated repeating the pushover analyses and comparing the results in terms of seismic safety index.

1 INTRODUCTION

Throughout Europe, a significant portion of the architectural landscape consists of unreinforced masonry buildings, many of which dated back to the past centuries, notably the Middle Age and Renaissance periods. These edifices were designed to support only vertical loads, disregarding horizontal forces. Consequently, they are very vulnerable to earthquakes, as evidenced by numerous devastating events occurred across the Mediterranean regions in recent decades, like those happened in Morocco and Turkey (2023) and Greece (2020) [1 - 3].

Earthquakes provoke the loss of a great number of human lives and significant damages to the existing heritage. In this context, the worst scenario is represented by the partial or global collapse of the buildings. Other phenomena include horizontal or vertical bending due to the configuration of the roof or the thrust of internal masonry vaults and arches, respectively. These vulnerabilities derive from the absence of the so - called "box behaviour", which entails creating a structure capable of withstanding seismic forces. It involves creating connections between masonry walls and among panels and horizontal floors [4, 5]. Another critical aspect of masonry buildings is their arrangement: they can be constructed as isolated structures or as clustered ones, in the latter case forming compounds that consist of multiple units variably interconnected to each other. Typically, the cells within an aggregate originate from different time periods, resulting in a mix of materials. This heterogeneity can lead to staggered floors, causing vertical bending phenomena along the boundary walls [6 – 8].

Assessing the seismic vulnerability of masonry structures, whether in isolated form or aggregated, represents a challenging task in the engineering field due to several factors, including lack of information regarding the materials used in the construction [9 - 11]. Many of these structures were built without a detailed project, using only the skills of the workers involved. Beside the limitations of the knowledge, another complexity is the evaluation of the interaction among the single structural units, since the dynamic response and capacity of one cell are strongly correlated with the presence of neighbouring units. A further challenge lies in selecting appropriate calculation software capable of taking into account the heterogeneity of masonry aggregates. Due to these multiple difficulties, the seismic evaluation of compounds remains relatively underexplored in the scientific community. Nonetheless, over recent decades, researchers developed various approaches to analyse these constructions, combining empirical techniques with mechanical ones [12 - 15].

Considering the age of existing buildings and their placement in areas prone to high seismic activity such as Italy, Portugal, Greece, and the Balkan area including Romania and Croatia, there is an urgent need for a consolidation plan which is essential to enhance the seismic resilience of these structures and prevent future catastrophic damages.

In addition to the most traditional retrofitting techniques, recent years have seen the appearance of new and innovative solutions in the construction market. Among these innovations, composite materials and coating systems stand out [16 - 18]. In particular, focusing on envelope systems, they consist of metal exoskeletons coupled with insulating panels which contribute at improving energy aspect in addition to seismic performance upgrading [19, 20]. In fact, it is important to note that beside inadequate seismic response, these ancient constructions may also suffer from thermal dispersion originating from indoor environments. These issues were due to poor-quality materials or construction errors.

Several years ago, the EU defined some strategies to reduce CO_2 emissions aiming to mitigate climate change and promote a green revolution [21 – 23].

Based on these premises, the paper focused on the assessing the vulnerability of an existing masonry compound placed in Timişoara, a city in the western part of Romania. In order to investigate its seismic performance, static non - linear analyses were carried out using the 3Muri software. Since the seismic response appeared inadequate, a coating system consisting of metal exoskeletons and thermal insulating panels arranged on the external facades of the compound was proposed and designed. Particularly, four different configurations of the arrangement of the integrated solution were compared to each other to find the optimal system.

2 THE CITY OF TIMIŞOARA AND THE MASONRY COMPOUND UNDER STUDY

2.1 The centre of Timişoara and its historical evolution

Timişoara is one of the most important cities in Romania. It is placed in the western part of the country and is the capital city of the Timiş district in the historical region of Banat. The city's history, which is characterized by the succession of numerous events, has very ancient origins, dating back to the half part of the 10th century. The city experienced a flourishing period in the 14th century and, a few centuries later, with Eugene of Savoy, who began the construction of many palaces in Baroque style. During the same period, the city assumed a central commercial role due to its strategic position along the Bega river. Today, the city is an important university center, and was chosen as the European Capital of Culture in 2021 in order to enliven the cultural landscape [24].

2.2 Seismicity of the Banat region

The masonry complex under investigation is placed in Timişoara within the Banat region, which has a moderate seismicity and is characterized by shallow earthquakes of crustal type. The seismic risk map is shown in **Figure 1,** which highlights the PGA according to the Romanian Technical Code [28]. In the region considered, the maximum ground acceleration can range from 0,15g to 0,20g [25 - 27] and the maximum magnitude recorded for occurred earthquakes was 5,6.

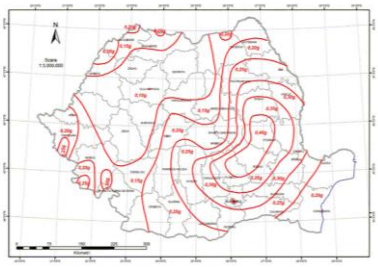


Figure 1: Seismic zonation: PGA for mean recurrence interval of 225ys and 20% exceedance probability in 50ys

2.3 The main features of the investigated masonry aggregate

The masonry aggregate is placed in the Iosefin district near the Cetate district. It is located next to the Water Tower, which was built around 1913 as a tank for the distribution of water for the entire city. The placement of the complex is represented in **Figure 2**.

Figure 2: Placement of the case study (in red) and historical city centre (in blue)

The Iosefin district was established as a village for German settlers, marked by the construction of large houses on both sides of the Bega river. The area is characterized by various types of buildings, ranging from single to three-storey structures. According to research conducted on the city of Timişoara by Moşoarca et al. [24], it is noteworthy that the majority of existing buildings in the area have a medium conservation status, while only 15% of the stock was consolidated. The masonry aggregate assumed as case study consists of ten structural units arranged in a linear configuration. It measures 125 m in length and 9,40 m in width, which widens to 11,15 m near the staircase blocks along the back façade. The whole aggregated complex has three levels above the ground floor (ground, first and second) and it has also an underground floor and a mansard on the top. It reaches a maximum height of 10,50 m above ground. The construction is entirely intended for residential use and was built at the beginning of the 20th century. The case study is also known as the "Ten Houses" (Or “Zece Case” in Romanian) due to its division into ten units. Each staircase block serves two apartments per floor (one on the right and one on the left). **Figure 3** shows the ground floor plan layout.

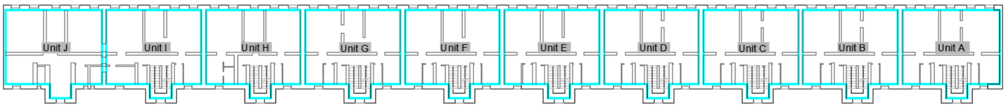


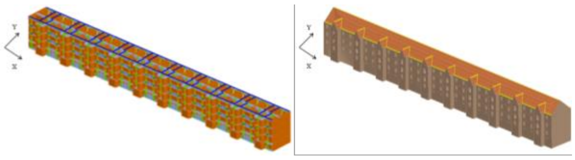
Figure 3: Ground floor plan layout

The structure represents a typical example of construction from the early 20th century: it is composed by three longitudinal walls, two along the facades, and the third serving as a median wall. Transverse walls are located at the boundaries between two modules. These walls have a thickness of about 60 cm and extend continuously from the base to the attic floor. The basement floor is covered by masonry vaults made of bricks, while the horizontal floors of the other levels consist of wooden beams measuring 20x30 cm and spaced 1 meter apart. The foundations and basement walls are constructed from stone masonry up to the point of intersection with the arches or vaults. From that level upwards, solid brick masonry is used.

3 THE SEISMIC BEHAVIOUR EVALUATION

3.1 Modelling phase with FME method

After all the geometrical, architectural, and structural information were acquired, the next step of the work involved the assessment of the seismic vulnerability of the masonry aggregate. This was conducted using the 3Muri software developed by the STA.DATA company. This calculation program ensures the evaluation of existing constructions, as well as of edifices having high cultural values, and the design of new ones. The program is based on a Frame by Macro - Elements approach (FME), which means that each masonry wall is schematized with an equivalent frame composed of three macro-elements: masonry piers, spandrels, and rigid nodes. Based on real damage observations, masonry piers placed between two subsequent openings and spandrels located above and/or under them represent the portions where deformability and damage are concentrated. Conversely, rigid nodes are usually free from damage, so that an infinitely rigid behaviour is assumed for them. **Figure 4** illustrates the created mesh of the building under investigation.



a) b)

Figure 4: a) The meshed building; b) Three-dimensional view of the aggregate

The modelling process started with the importation of the drawing file into the software so to draw the axis of the walls. Subsequently, thickness and typology were assigned to these panels. The adopted mechanical characteristics correspond to the lowest level of knowledge (KL1 – Limited Knowledge) according to the Eurocode 8 - Part 3 standard [29].

Afterward, openings were inserted, along with the horizontal internal floors and the roof that is composed by a timber frame made of wooden beams measuring 16x20 cm and tiles.

3.2 Results of non – linear analyses

To execute the non - linear analyses, the seismic actions were defined following the instructions given by Eurocode 8 standard, which defines two types of spectra: Type 1 for magnitudes greater than 5,5 and Type 2 for all other cases. The response spectrum for the Banat region was proposed by Gioncu and Mazzolani [30]. For the current case study, based on previous research, the Type 1 spectrum with a soil type C, characterized by sand deposits, was considered. An importance factor of 1 was assumed. Once the seismic actions were defined, pushover analyses were carried out, considering both gravitational loads and horizontal ones increasing monotonically. Analyses were performed monitoring the displacement of a control node near to the building centroid. **Table 1** contains the results related to the two worst conditions for each main direction related to the Significant Damage level (SD) in terms of α coefficient, that is defined as the ratio between capacity and demand PGA. The obtained results revealed the bad seismic performance of the building due to the low values of the α factor. **Figure 5** shows the pushover curves for the two main directions of the complex expressed in terms of base shear vs top displacement.

Table 1: Results of the pushover analyses

Nr	Earthquake Direction	Seismic load	Eccentricity [cm]	α_{SD}
14	-X	Uniform	-58,10	0,299
23	-Y	Static forces	625,50	0,175

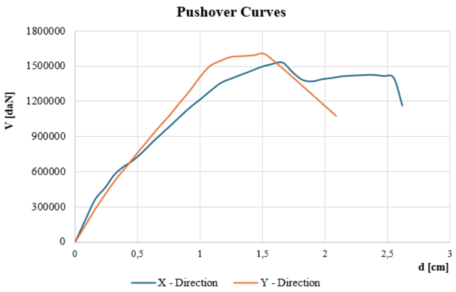


Figure 5: Pushover curves

Regarding the major damage mechanisms, spandrels along the main facade are affected by shear phenomena and elastic failure. For the masonry piers, the most common mechanism is shear with widespread compression – bending collapses that hit the ones located at ground floor.

4 THE RETROFITTING PHASE

4.1 The MIL15.s integrated seismic – energy coat

Non – linear analyses highlighted the inadequate seismic behaviour of the masonry aggregate which needs to be improved. For this reason, it was suggested to intervene on the building with an innovative system consisting of metal exoskeletons coupled with thermal insulation panels. Specifically, the used system is the MIL15.s one, manufactured by the Italian company TM Group S.r.l. and patented in May 2022. First of all, it represents a modern and innovative solution that fits into the category of other similar coating systems. The MIL15.s and all the other similar envelope systems embody an alternative retrofitting technique which allows for improving both seismic and energy performance of an existing building. They are applied externally to the construction ensuring a reduction in terms of both time and costs. In this way, it is possible to continue internal activities during works, that is a crucial aspect not only for inhabitants of residential buildings, but also for people in schools and offices. Indeed, the system is suitable for all the types of constructions made of either masonry or reinforced concrete. Coating systems have become widespread in the construction market only in recent years and are still less investigated in the literature [19]. Besides the lightweight solutions that use metal exoskeletons made of steel or aluminium alloy components, there are some options that foresee the realization of cast-in-place shear walls inside insulation panels that act as formwork. Focusing our attention on the MIL15.s system under study, **Figure 6** proposes a view illustrating all its main components.

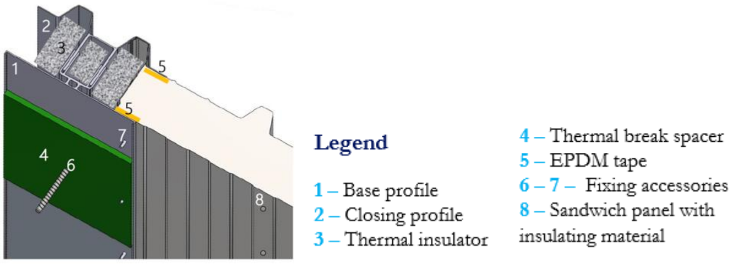


Figure 6: A view of the system

The solution consists of extruded aluminium alloy base profiles (Element nr. 1 in **Figure 6**) which are placed at variable distance one to each other (approximately 1 m) and fixed to the perimeter masonry panels using chemical anchors (El. nr. 6 in **Figure 6**). In the empty space between two subsequent vertical profiles is inserted the thermal insulation panel (El. nr. 8 in **Figure 6**). Typically, it is a sandwich panel having a trapezoidal external and internal sheeting, anchored with self – drilling screws. The insulating material could be rockwool or polyurethane. Finally, the integrated system is completed with the placement of the closing profiles (El. nr. 2 in **Figure 6**). In order to avoid other thermal dispersions, the EPDM tape and thermal insulator (El. nr. 5 and 3, respectively, in **Figure 6**) are used. The aluminium alloy used for the profiles is alloy AW6060 – T6 which has a characteristic 0,2 proof strength equal to 150 MPa and an ultimate tensile strength of 190 MPa [31]. The decision to use aluminium for the system's components is driven by its numerous advantages. Firstly, aluminium is a lightweight material, with a specific weight that is three times lower than that of steel. Secondly, it showcases exceptional resistance to corrosion due to the formation of a thin, protective layer of aluminium oxide on its external surface [32, 33], therefore showing high durability over time. Thirdly, one of the most significant properties of aluminium alloy is its sustainability. Indeed, structural aluminium is fully recyclable without any loss of quality, making its recyclability crucial from both environmental and economic perspectives. In fact, producing new aluminium alloy components from recycled materials requires significantly less energy and results in lower greenhouse gas emissions [34].

4.2 Design of the system and its arrangement on the facades

To evaluate its influence on the masonry aggregate under investigation, which exhibited a deficient seismic behaviour, the aforementioned solution has been proposed as an integrated retrofitting technique. In the software, the MIL15.s was schematized using a simplified approach with an equivalent frame in correspondence of each masonry pier at every level. Particularly for modelling purposes, the numerous sandwich panels within the different modules, which act as seismic devices, are incorporated as a single equivalent diagonal having a full circular cross-section. The estimation of the diagonal diameter to be inserted in the calculation software has been obtained determining the equivalent system stiffness using the following equation according to previous literature research [35, 36]:

$$Keq = \Sigma Ki \tag{1}$$

where K_i is the stiffness of each diagonal representing the sandwich panel connected to each masonry pier. Therefore, starting from the equivalent stiffness, it has possible to derive the area A_p, and then, the diameter φ, of the equivalent diagonal by means of the following formulation:

$$Keq = Ep \cdot Ap/lp \cdot cos2\alpha \tag{2}$$

where:

- $E_p = E_s$ is the elastic modulus of the material.
- l_p = equivalent length, equal to b/cosα, being b the frame width, h the frame height and α = arctg h/b (see the parameters illustrated in **Figure 7**).

From eq. (2), the relationship for the calculation of the area could be easily derived.

Once calculated the bracing area, the diameter ϕ can be found through the formula (3):

$$\varphi = \sqrt{(4 \cdot Ap)/\pi} \tag{3}$$

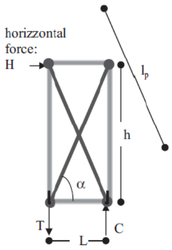


Figure 7: Geometrical parameters used for design phase of the equivalent diagonal

4.3 Comparison of results among four different configurations

Four different arrangements of the seismic coat on the building facades were considered to find the best solution for retrofitting the case study aggregate. In particular, the following cases were taken into account:

- Case 1: Seismic coat applied only to the two heading SUs on the free facades;
- Case 2: Seismic coat applied only to two internal SUs in the middle of the aggregate;
- Case 3: Combination of Case 1 and Case 2;
- Case 4: Seismic coat installed on the entire masonry aggregate.

Figure 8 display these four conditions.

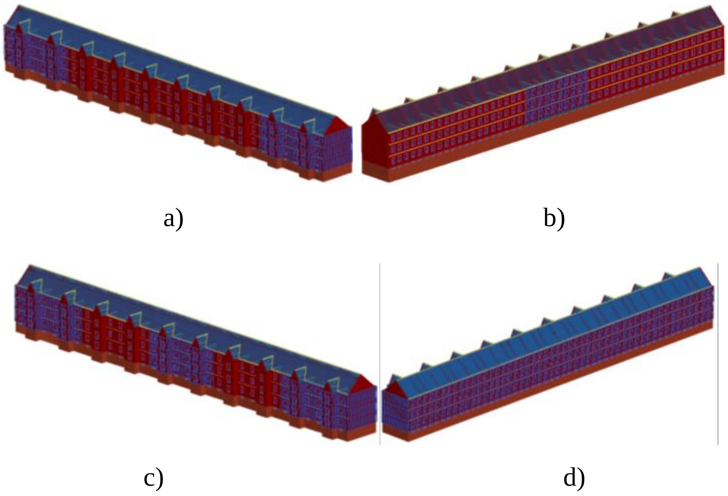


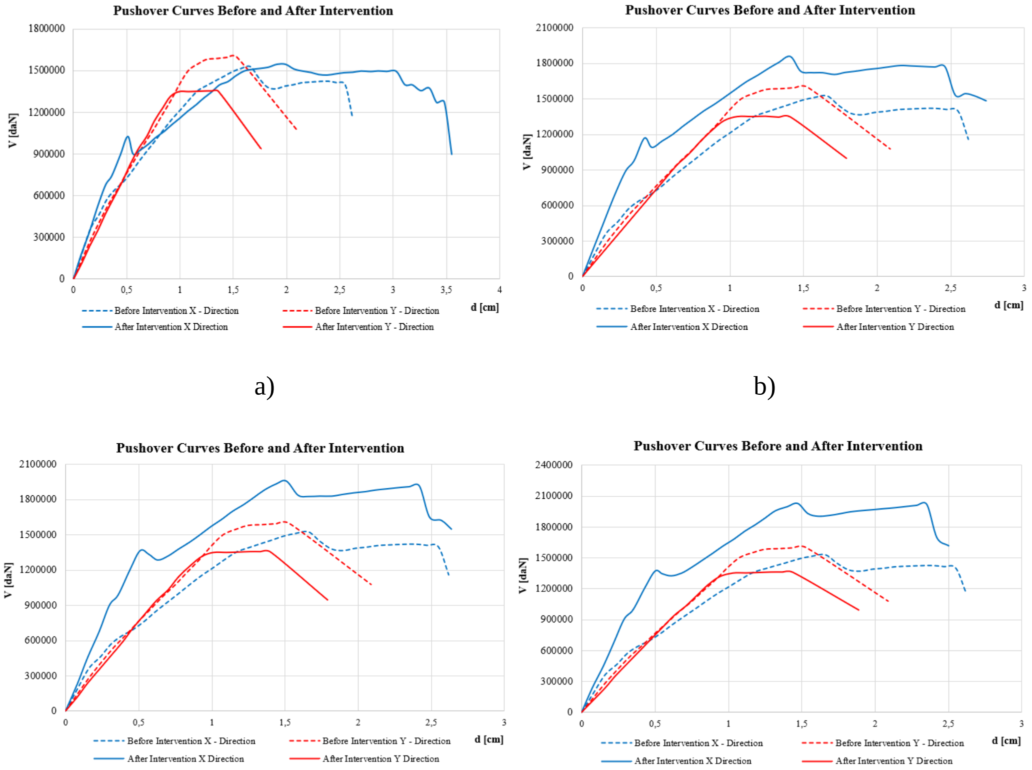
Figure 8: Four configurations: a) Case 1 (Back façade); b) Case 2 (Main façade); c) Case 3 (Back façade); d) Case 4 (Main façade)

Once the four retrofitted models were created implementing the seismic coat, static non – linear analyses were repeated under the same conditions described in previous chapter.

Table 2 contains the worst results in the two analysis directions for each case analysed. Along the longitudinal direction (X), the seismic upgrading was achieved thanks to the increase at least of 0,1 of the seismic safety factor. Contrary, in the transverse direction (Y), the factor slightly increases, but it does not allow to attain the seismic upgrading. In the X direction the best solution is represented by the Case 2, while for the other direction by the Case 4.

Table 2: Comparison of the results among four different configurations

Retrofitted Configuration	Earthquake Direction	α_{SD}
1	X	0,497
	Y	0,215
2	X	0,523
	Y	0,213
3	X	0,503
	Y	0,218
4	X	0,499
	Y	0,221



a) b)

c) d)

Figure 9: Comparison of pushover curves for the four configurations: a) Case 1; b) Case 2; c) Case 3; d) Case 4

Pushover curves, plotted in **Figure 9**, highlight the comparison before and after the application of the seismic coat. Particularly, it is possible to observe that along the direction X (the longest one), there is a significant increase in terms of stiffness and resistance with an attainment of higher values of shear and a moderate improvement in ultimate displacement. On contrary, along the shortest direction (Y axis), the application of the seismic coat provokes a slight increase in terms of α coefficient, while the pushover curves seem not to reflect this condition, showing a decrease of resistance.

5 CONCLUSIONS

The current work dealt with the investigation of the seismic vulnerability of an existing masonry compound placed in Timişoara, a city located in the high seismic area of the Banat region within Romania.

The masonry aggregate is composed of ten structural units erected in continuity one to each other sharing the boundary walls and articulated in three levels above ground. The knowledge phase allowed to study its main structural properties necessary to carry out the analysis process. Specifically, the structure is made of brick masonry and it is covered in correspondence of the underground floor by masonry vaults, while the level upwards show a horizontal slab realized with wooden beams.

Afterwards the model on the 3Muri calculation software was created, static non – linear analyses were performed by considering 24 load combinations according to the Eurocode 8 standard. The pushover curves and the α coefficient relative to the Significant Damage Level pointed out the inadequate seismic response of the clustered building under investigation.

In order to improve its seismic performance, an innovative solution, consisting of metal exoskeletons made of aluminium alloy and coupled with insulating panels, was designed and implemented in the software using a simplified approach with an equivalent diagonal bracing. Particularly, four combinations in the arrangement of the coating system on the compound facades were considered and compared to each other.

Non – linear analyses were repeated for all the configurations and the results demonstrate the benefit corresponding to this insertion especially along direction X with an increase of both the α coefficient, so to achieve the seismic upgrading, and resistance. On contrary, for the direction Y, the used retrofit solution did not provoke a significant enhancement in terms of seismic safety.

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