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# NUMERICAL STUDY ON THE HYGROTHERMAL BEHAVIOUR OF RETROFITTED HISTORICAL MASONRY BUILDINGS

BY

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**Abstract.** Most of the Romanian buildings built before 1940 are unreinforced masonry structures. These buildings do not satisfy the current provisions regarding structural safety and thermal insulation and require retrofitting works. As some of these buildings contribute to the country's architectural heritage, the retrofitting solutions must preserve the existing facade. The exterior walls are usually strengthened with concrete jacketing and an internal thermal insulation system is sometimes provided. The internal thermal insulation system may cause moisture accumulation within the wall which can lead to premature deterioration. This paper analyses the hygrothermal behaviour of retrofitted exterior unreinforced masonry walls. Numerical simulations are made for typical existing walls configurations and retrofitting systems. The effect of the thermal insulation on the moisture accumulation within the wall is analysed for three Romanian cities. Comparisons are made with the in-force Romanian and European regulations provisions.

**Key words:** concrete jacketing; thermal insulation; water vapour condensation; saturation pressure; moisture accumulation.

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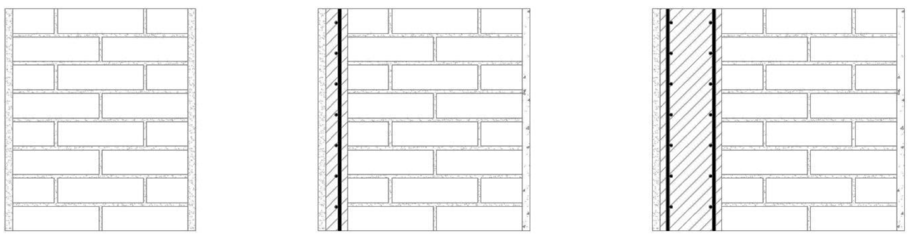
## 1. Introduction

In 1992, in Romania, the masonry structures represented 35% of all the existing buildings (P100-3/2008), with 440.000 buildings built before the Second World War (P100-3/2008). Some of these buildings are in cities with high seismic hazard. For instance, in Bucharest, in 1992 existed 38.400 masonry buildings built before 1944, only 45% of them having reinforced concrete slabs (Georgescu, 1999). These historical buildings are very susceptible to damage and prone to partial or total collapse when undergoing seismic actions as they were only designed for vertical loads. In fact, in Romania, the earthquake loads were only considered after the 1940 earthquake for the public buildings.

For these old masonry buildings, the current building practice was to have for the interior walls a thickness of 1, 1.5 or 2 bricks, depending on the number of levels. The exterior walls had a minimum thickness of 1.5 bricks in order to ensure a better thermal protection of the interior, with up to 2.5 bricks for medium rise buildings. The bricks used before 1940 were generally 28 × 14 × × 8 cm bricks and the mortars were lime-based, without added cement. The most used solution for strengthening the masonry walls in Romania consist in applying steel mesh reinforced plastering on one or both sides of the wall. For medium rise buildings with wide masonry walls, a reinforced concrete jacketing is generally placed adjacent to the existing wall, the minimum thickness of this new shear wall depending on the design stresses as well as on constructive conditions (Fig. 1).



*a* *b* *c*

Fig. 1 – Typical strengthening solutions for masonry walls
*a* – Initial masonry wall; *b* – Strengthening by reinforced plastering; *c* – Strengthening by reinforced concrete jacketing.

Furthermore, thermal retrofitting is also needed for the old masonry buildings, in the context of the European target of reducing energy consumption stated in the 2010/31/EU Directive. This directive emphasises that when existing buildings undergo major renovation or when a part of the envelope is retrofitted measures should be taken in order to also improve its energy performance. In the general context of retrofitting the buildings from a structural point of view, it is normal to also take measures in order to improve the energy consumption, the most commonly applied measures consisting in installing thermal insulation, replacing the glazing, improving air-tightness and introducing mechanical ventilation with heat recovery.

There are multiple solutions of improving thermal insulations of the outer walls for existing buildings (Ma *et al*., 2012). Placing an additional thermal insulation on the external side of the building envelope is generally the best solution (Kossecka & Kosny, 2002; Kolaitis *et al*., 2013; Karagiozis & Salonvaara, 2001), as the structure is more protected from environmental loads, the thermal bridges are practically eliminated and the installation is simple.

These solutions cannot always be used for old buildings. In Romania, some of the heritage buildings are included in the category of historical monuments, which are protected by law. For these buildings, the general regulations for seismic retrofitting (P100-3/2008) do not apply. Also, the European Directive on the energy performance of the buildings (Directive 2010/31/EU) clearly specifies that thermal retrofitting requirements do not apply to buildings officially protected as part of a designated environment or because of their special architectural or historical merit.

Ensuring energy efficiency and architectural heritage for masonry buildings can be a hard challenge (Fabbri, 2013). In order to also provide structural safety, while preserving the historical buildings for future generations may require non-conventional solutions. In particular for the buildings on the historical monuments list (List of Historical Monuments, 2010), but also for the buildings in their vicinity, in the so-called protection area, interventions that may alter the old facades are generally not allowed.

For these buildings, the seismic retrofitting jackets are placed only on the inside of the facade walls. The additional thermal insulation, when used, has to be also placed on the inside of the wall. It is not always possible to add a RC jacket and also an internal thermal insulation, as this would lead to an important loss of internal space.

The interior insulation of massive masonry can lead to potential problems related to condensation of water vapour (Vereecken & Roels, 2014). The water-vapour concentration difference between the two sides of the exterior wall determines a water-vapour migration through it. During the winter, the insulation layer on the inside determines an important drop of temperature in this layer, while the temperature of the masonry remains very low. If in one layer the temperature is below the dew point, condensation can occur. Condensation can lead to many damage patterns such as mould growth (Johansson *et al*., 2010), migration and crystallisation of soluble salts (Steiger *et al*., 2011), decay of wood elements (Brites *et al*., 2013), and corrosion of steel elements (Bertolini *et al.*, 2013). The presence of water within the masonry negatively affects its compressive and shear strength (Gentilini *et al.*, 2012) and exposes the material to freeze-thaw cycles which can cause even further damage (Kvande & Lisø, 2009).

These damage patterns are particularly dangerous as they might worsen the safety of the building in case of earthquake event. An often recommended solution that diminishes the risk of condensation consists of using a vapour barrier on the inside face of the insulation. Still, the water vapour barriers are not a perfect solution (Toman *et al.*, 2009). First of all, they are very sensitive to mechanical damage and any bolt used for anchoring the furniture to the walls to avoid it from falling during earthquakes could lead in time to eventual vapour condensation. Second, a vapour tight system might cause other moisture related damages like the decay of wooden beam ends (Morelli & Svendsen, 2013). Finally, a higher vapour tightness of the envelope requires increased demands for efficient ventilation to preserve hygrothermal comfort inside the building and a mechanical ventilation system is usually difficult to integrate into a historical building.

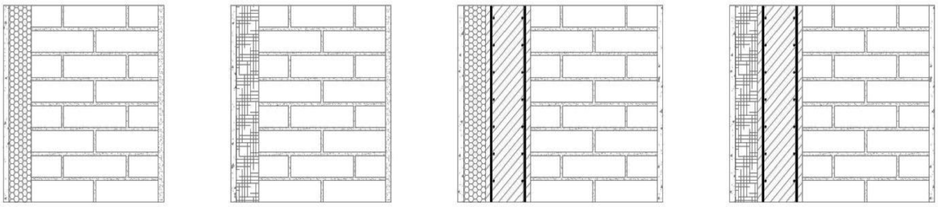
It is clear that choosing the thermal retrofitting solution for a historical masonry building requires an in depth study of its influence on the wall's hygrothermal performance and that an inadequate solution could lead to premature failures.

In this paper, the hygrothermal behaviour of old masonry walls is analysed. Four scenarios with different hypothesis are considered. The first consists of the original, non-retrofitted wall. For the second scenario, only the structural retrofit of the wall is taken into account. For the third scenario, the wall only has additional thermal insulation added, without seismic strengthening. In the last scenario, a fully retrofitted wall is considered.

For each of the considered cases, a mathematical model of the wall is made and the variations of temperature and vapour partial pressure inside the wall are computed. The quantities of condensed vapour are evaluated. The risks concerning water accumulation and freeze-thaw cycles are assessed.

Three representative historical cities of Romania are considered in this paper: Bucharest, Iasi and Brasov. The choice is based on the fact that the centres of these cities have many architectural heritage buildings and the climate conditions are different, according to climatic zoning of Romania (MC001/6-2013).

There are multiple materials currently used for the thermal retrofitting of old buildings (Jelle, 2011), with different behaviours between the various solutions (Rasmussen & Nicolajsen, 2007). In the present study, expanded polystyrene (EPS) and mineral wool are considered for the insulating layer. The general solutions considered are shown in Fig. 2.



*a* *b* *c* *d*

Fig. 2 – Hygrothermal rehabilitation of masonry walls:
*a* – Masonry wall with EPS; *b* – Masonry wall with mineral wool;
*c* – Masonry wall with RC jacket and EPS; *d* – Masonry wall with RC jacket and mineral wool.

## 2. Considered Parameters for the Modelling of the Hygrothermal Behaviour

In the modelling of heat and vapour transfer, the following assumptions are made: one dimensional heat and mass transfer, plane geometry, steady-state conditions and constant properties.

The differential equation of heat conduction in stationary thermal regime is:

$$\frac{\partial^2 \theta}{\partial x^2} = 0, \tag{1}$$

In the numerical model it is considered that the envelope element consists of multiple plane layers, parallel to each other and perpendicular on the direction of heat and vapour flow. The same width is considered for all the layers.

The temperature in layer "j" of the heterogeneous multilayer envelope element is:

$$\theta_j = \theta_{si} - \frac{R_{si} + R_1 + ... + R_{j-1}}{R_T}\left(t_i - t_e\right) \tag{2}$$

where: $t_i$ and $t_e$ are the interior and respectively exterior temperatures; $\theta_{si}$ – the temperature on the interior face of the envelope element; $R_{si}$ – the interior heat transfer resistance; $R_T$ – the total thermal resistance; $R_j$ – the thermal resistances of the *j* layer.

The variation of partial pressure of water vapour that enters through diffusion in the envelope element can be written in a similar manner, using Fick's law:

$$p_j = p_i - \frac{R_{v1} + \ldots + R_{vj-1}}{\sum_{k=1}^{n} R_{vk}} (p_i - p_e), \tag{3}$$

where: $p_i$ and $p_e$ are the interior and respectively exterior vapour partial pressures; $p_j$ – the vapour partial pressure in layer $j$; $R_{vj}$ – the vapour resistance of the material forming layer $j$.

**Table 1**
*Climatic Parameters*

| Month | Bucharest | | Iaşi | | Braşov | |
|---|---|---|---|---|---|---|
| | $t_e$, [°C] | $\varphi_e$, [%] | $t_e$, [°C] | $\varphi_e$, [%] | $t_e$, [°C] | $\varphi_e$, [%] |
| January | –1.2 | 87.7 | –2.1 | 84.0 | –3.3 | 88.1 |
| February | 1.2 | 81.3 | –0.1 | 77.9 | –1.9 | 82.9 |
| March | 5.6 | 73.9 | 4.3 | 70.0 | 2.7 | 75.8 |
| April | 11.3 | 72.5 | 10.8 | 65.3 | 8.5 | 72.5 |
| May | 17.5 | 70.1 | 16.9 | 61.6 | 14.2 | 72.1 |
| June | 21.4 | 70.0 | 20.4 | 63.2 | 17.4 | 73.7 |
| July | 23.4 | 68.0 | 22.3 | 65.3 | 19.1 | 73.9 |
| August | 22.5 | 69.9 | 21.1 | 67.9 | 18.2 | 76.5 |
| September | 16.8 | 75.8 | 15.6 | 73.1 | 13.2 | 80.0 |
| October | 11.1 | 81.5 | 10.3 | 77.2 | 8.4 | 81.8 |
| November | 5.2 | 86.1 | 4.4 | 82.3 | 2.7 | 84.2 |
| December | –0.2 | 88.3 | –1.2 | 84.7 | –2.8 | 87.8 |

For each of the layers considered in the model, the temperature is evaluated using eq. (2) and the corresponding local saturation pressure is calculated. In each layer, the partial pressure of water-vapour is evaluated using eq. (3) and its value is compared with the saturation pressure to identify the risk of condensation inside the element. Tracing the saturation pressure and partial pressure variations on the same diagram allows a graphical analysis of the phenomenon.

The external climatic parameters $t_e$ and $\varphi_e$ (Table 1) are considered in accordance with the Romanian regulation on the assessment of the energy performance of the buildings, MC 001/ 6-2013. The interior parameters $t_i$ and $\varphi_i$ are set to 20°C and 60% respectively. The analysis of the behaviour of the current field wall in terms of diffusion of water vapour for various constructive solutions is performed according to SR EN ISO 13788.

The hygrothermal characteristics of the materials considered for the parametrical study are chosen in accordance with Romanian C107-2005 regulation. These characteristics are shown in Table 2.

**Table 2**
*Hygrothermal Characteristics of the Materials*

| Material | Thermal conductivity (W/mK) $\lambda$ | Factor of resistance to vapour diffusion $\mu$ |
|---|---|---|
| Solid brick masonry | 0.8 | 6.1 |
| Lime mortar for plastering | 0.7 | 5.3 |
| Cement mortar for jacketing | 0.93 | 7.1 |
| Reinforced concrete for jacketing | 1.74 | 21.3 |
| Cellular expanded polystyrene | 0.044 | 30 |
| Mineral wool | 0.04 | 2.4 |
| Water vapour barrier (polyethylene layer) | – | 50,000 |
| Plasterboard | 0.41 | 6.1 |

## 3. Numerical Analysis of the Hygrothermal Behaviour of the Exterior Walls

### 3.1. Non-Retrofitted Historical Buildings

The water vapour diffusion through a 1.5 bricks masonry wall is analysed. The masonry is considered to be 43 cm thick (the dimensions of the old bricks are 28 × 14 × 8 cm), and the coating on the inside and outside faces is considered to be done with lime plastering, 2 cm thick. The analyses are performed for the 3 cities mentioned above, for each month of the year. The results are shown for January, which is the coldest month of the year.

For the non-retrofitted wall, there is no risk of vapour condensation inside the walls, but the temperature in the outer layers of masonry (as shown in Fig. 4) are below freezing point even when considering average monthly temperatures.

### 3.2. Thermally Retrofitted Historical Buildings

Sometimes the owners of old buildings only invest in the thermal retrofit of the buildings, without structurally strengthening. This is due to the high costs related to maintaining thermal comfort in old buildings, which could be diminished by additional insulation, while private owners generally lack the funds for a full renovation of the building.

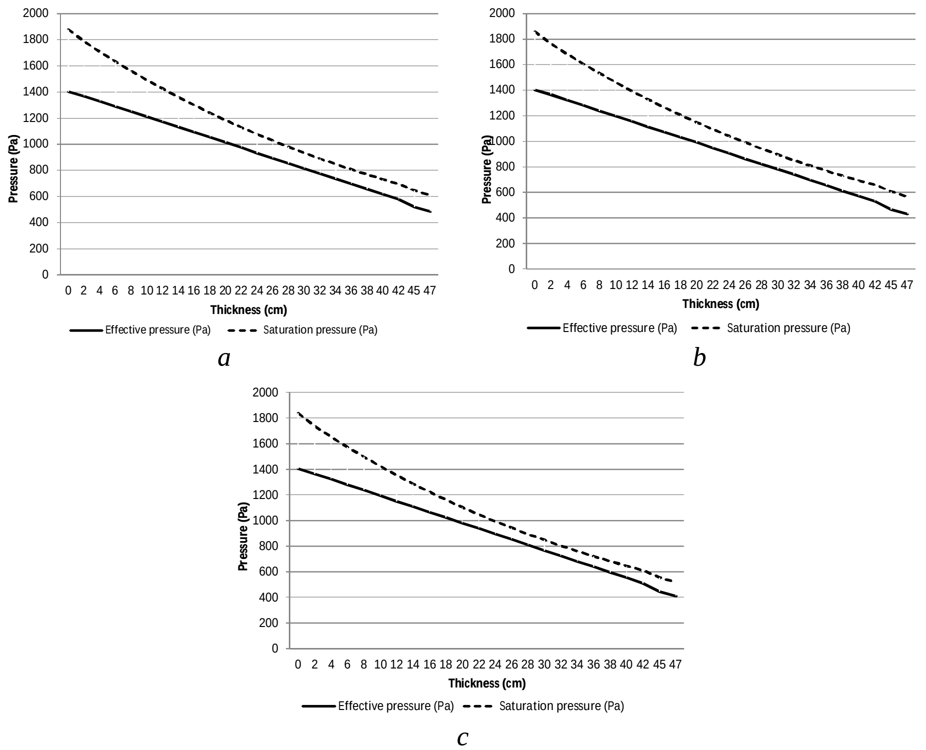



Fig. 3 – Variation of the saturation pressure and effective pressure of diffused water vapours for a non-retrofitted exterior masonry wall in January in *a* – Bucharest ; *b* – Iaşi; *c* – Braşov.

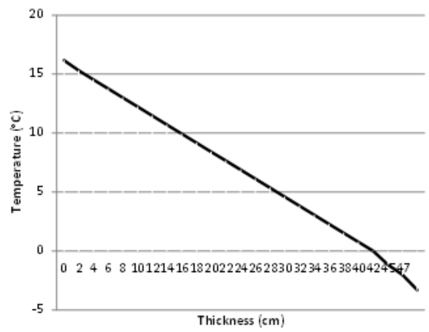
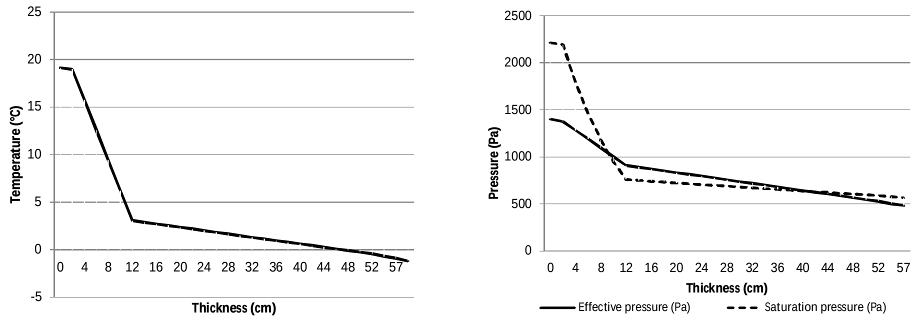



Fig. 4 – Variation of the temperatures in January in an exterior masonry wall in Braşov.

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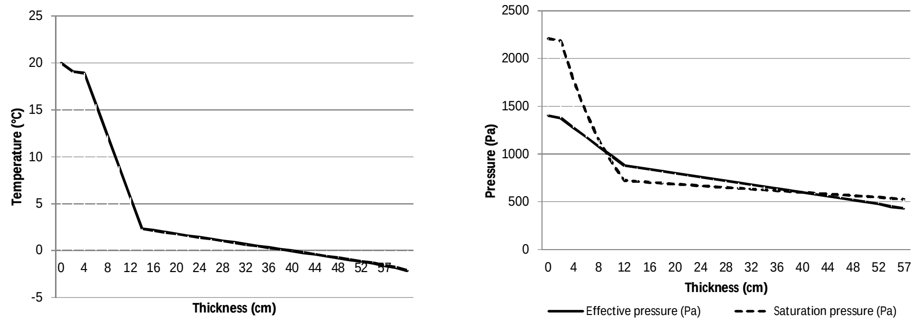


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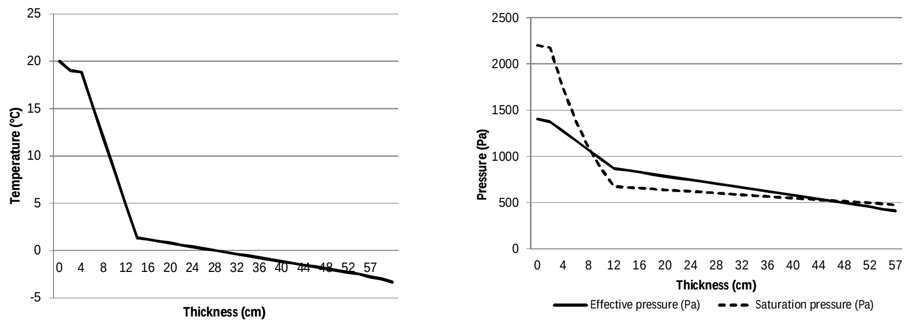



*c*

Fig. 5 – Temperature variation (left) and variation of the saturation pressure and effective pressure of diffused water vapours (right) in January in *a* – Bucharest; *b* – Iaşi; *c* – Braşov for thermally retroffited wall.

The fastest and less expensive solution is to bond on the inside of the wall a 10 cm thick layer of expanded polystyrene, finished with a suitable plaster. The temperature and vapour pressure diffusion diagrams are modified from their original form (Fig. 5).

The retrofitted wall provides better thermal protection, but condensation of vapour occurs inside the thermal insulation and masonry. When using for computation the average values of climatic parameters, the phenomenon occurs during all the winter months: December, January and February. As the outside temperature may be, in certain periods, much lower than the monthly average, the temperature of the masonry can reach negative temperatures and condensed water vapour can freeze, increasing its volume. Repeated freeze-thaw cycles can negatively affect the physical and mechanical properties of masonry.

### 3.3. Seismically Retrofitted Historical Buildings

Most of the times, the refurbishment of historical masonry buildings has as main purpose the structural strengthening, because life safety is a major concern. The old masonry buildings have generally suffered structural damage due to earthquake loads, but also due to other factors. Not always is it possible to also add a thermal insulation, as this might further reduce the internal space of the building and make it unusable.

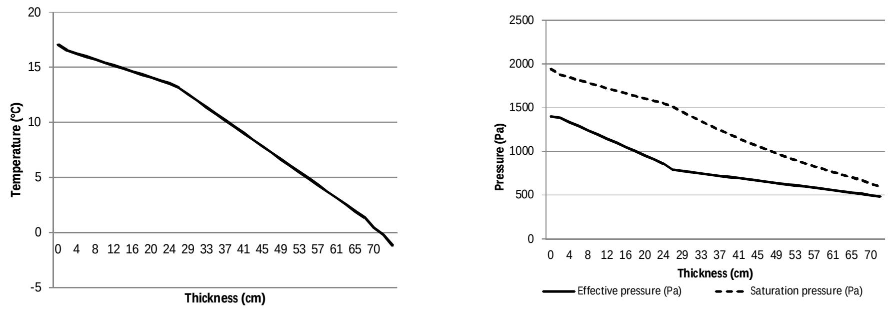
A 25 cm concrete jacket on the inside of the wall was considered. The temperature and vapour pressure variation diagrams are shown in Fig. 6. There is no significant difference for the hygrothermal behaviour between the structurally strengthened wall and the original one. Even if there is an increase of the total thermal resistance it is still very low with regard to the minimum resistance required for the new buildings.

### 3.4. Fully Retrofitted Historical Buildings

Three solutions for the full (structural and hygrothermal) retrofit of the wall are considered. For all the cases, the considered structural retrofit consists in an additional RC jacket 25 cm thick on the inner face of the old masonry wall.

**The first solution** includes as additional insulation a layer of 10 cm EPS. The diagrams for temperature and vapour variations are shown in Fig. 7.

For this solution, condensation occurs inside the EPS and concrete layers. Using monthly averages for the climatic parameters, condensation occurs from November till March. The maximum difference between effective pressure and saturation pressure, in the condensation area, is 343 Pa for Bucharest, 366 Pa for Iaşi and 408 for Braşov. The accumulated water during the cold season reaches a maximum value of 774 g/m$^2$ (in Braşov), but the wall loses this quantity in spring and summer months.

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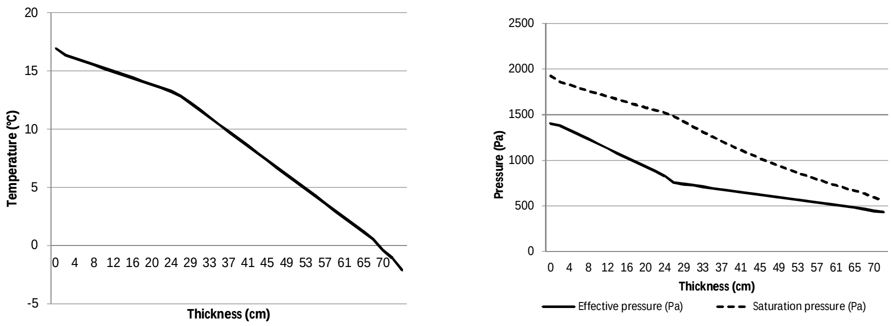


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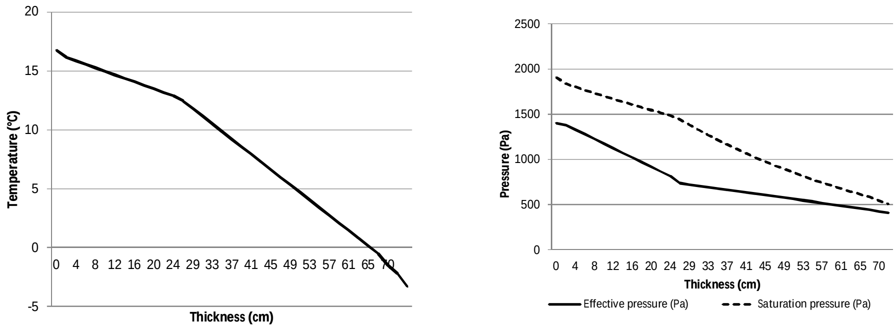
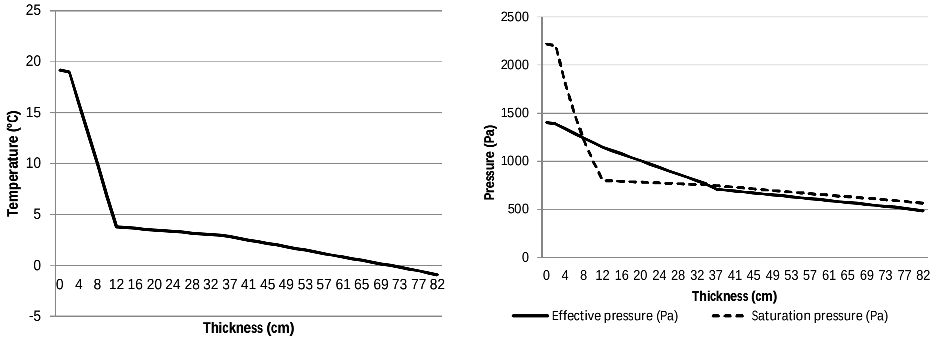



*c*

Fig. 6 – Temperature variation (left) and variation of the saturation pressure and effective pressure of diffused water vapours (right) in January for seismically retrofitted wall in *a* – Bucharest; *b* – Iaşi; *c* – Braşov.

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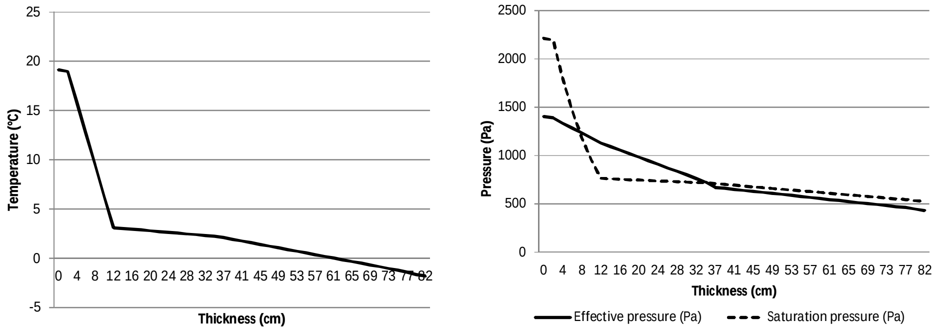


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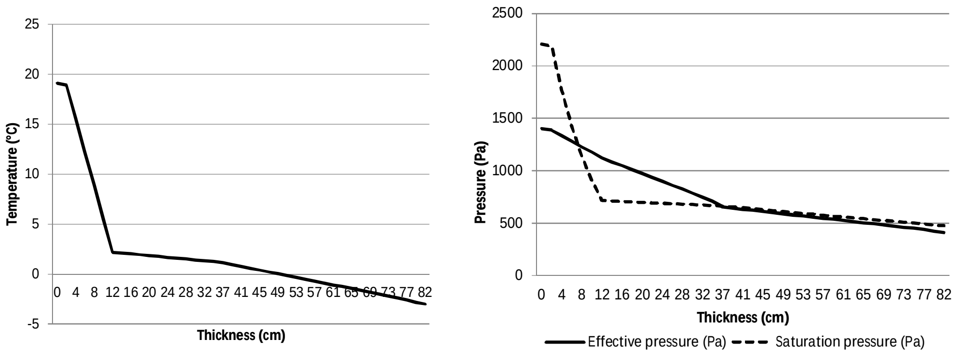


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Fig. 7 – Temperature variation (left) and variation of the saturation pressure and effective pressure of diffused water vapours (right) in January for EPS+RC wall in *a* – Bucharest; *b* – Iași; *c* – Brașov.

**The second solution** includes as additional insulation a layer of 10 cm mineral wool with a vapour barrier layer on the warm (inside) face of the thermal insulation. On the inside, a plaster board finishing is considered. The diagrams for temperature and vapour variations are shown in Fig. 8.

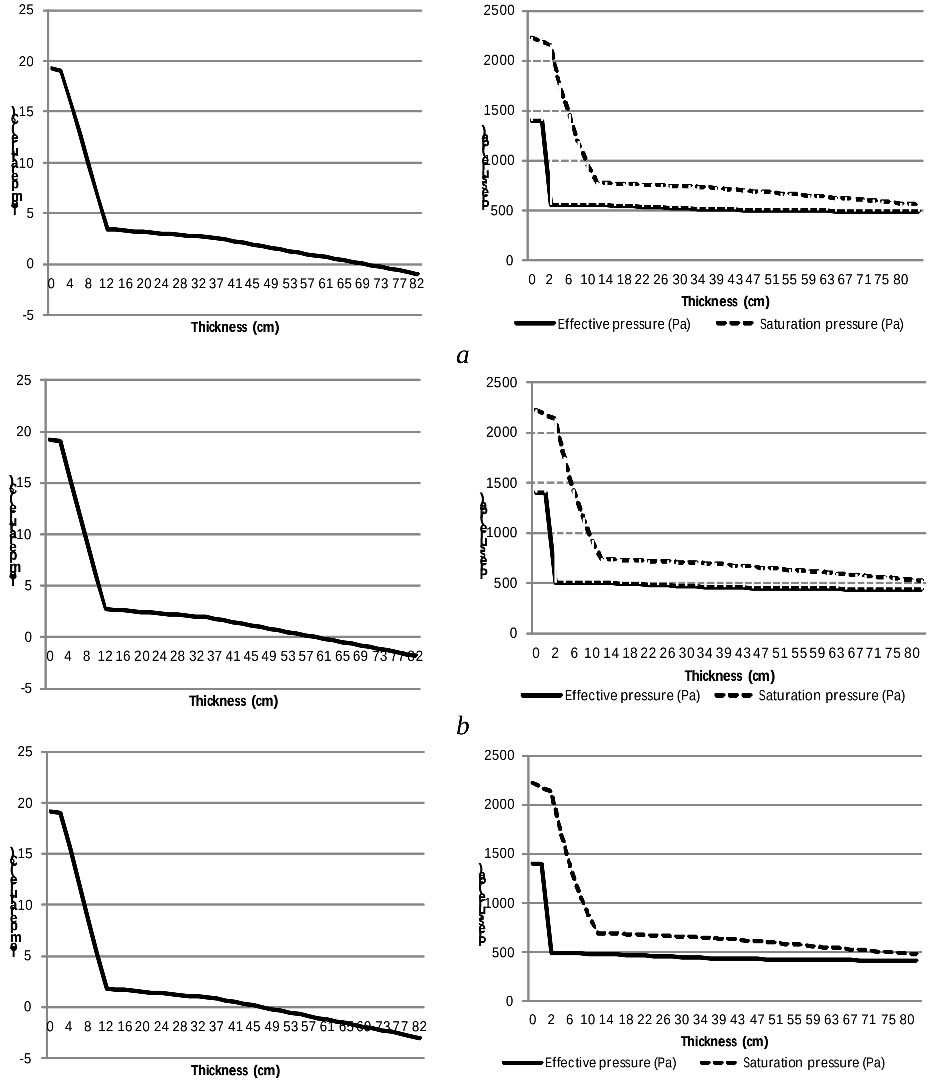


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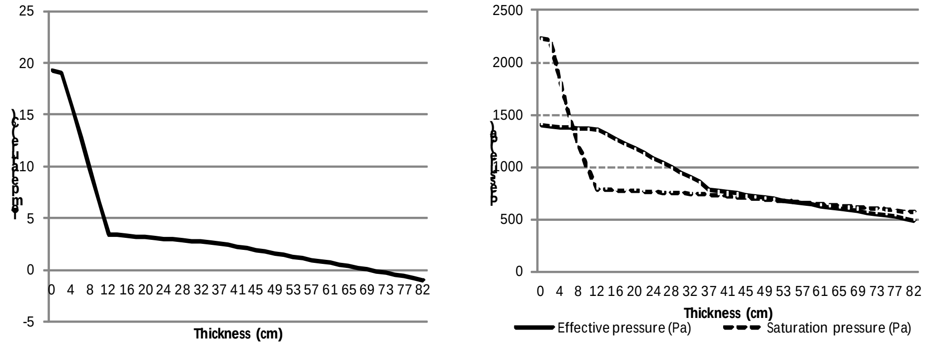
Fig. 8 – Temperature variation (left) and variation of the saturation pressure and effective pressure of diffused water vapours (right) in January for VB + MW + RC in *a* – Bucharest; *b* – Iaşi; *c* – Braşov.

The diagrams show that the wall has a good behaviour concerning vapour diffusion, as the saturation pressure and partial vapour pressure graphs do not intersect. The problems of the thermal bridges and of the indoor environmental quality still need to be addressed, given that indoor air will contain a larger amount of water vapour that cannot be eliminated through walls. Using a ventilation system and air fresheners can help maintaining adequate relative humidity values.

**The third solution** is similar to the second, but without the vapour barrier layer. The diagrams for temperature and vapour variations are shown in Fig. 9.

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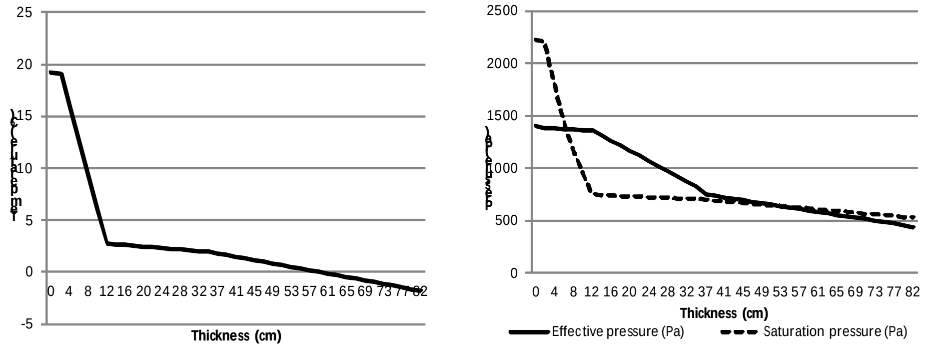


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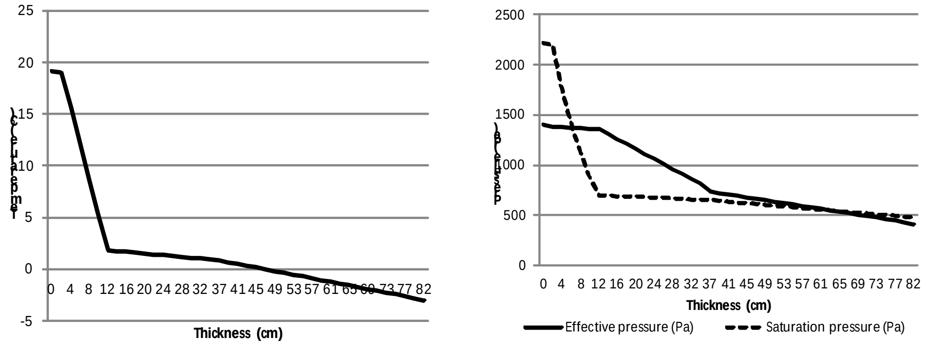


*c*

Fig. 9 – Temperature variation (left) and variation of the saturation pressure and effective pressure of diffused water vapours (right) in January for MW + RC in *a* – Bucharest; *b* – Iași; *c* – Brașov.

The temperature variations diagrams are practically the same as before, because the vapour barrier is extremely thin and has practically no influence on heat transfer. Regarding vapour diffusion, there is a very big difference between the solution with vapour barrier (Fig. 8) and without (Fig. 9). In the latter case, condensation occurs inside the wall from November till April, for average climatic conditions. The affected layers are the thermal insulation, the concrete jacketing as well as the masonry. The quantity of accumulated water during the cold season has very high values, of 2.78 kg/m$^2$ in Bucharest, 3.11 kg/m$^2$ for Iasi and 3.77 kg/m$^2$ in Brasov. For Bucharest and Iasi, the wall dries in the spring and summer months, but for Brasov there is a net yearly accumulation of moisture inside the wall.

## 4. Conclusions

The retrofit of historical buildings is an intricate issue. The structural and stability strengthening and the improved thermal comfort must be achieved while preserving in good conditions the historical and cultural heritage. Based on the numerical study, some important conclusions can be drawn regarding the choice of the retrofitting solutions:

1) Retrofitting works must be done, mostly, inside the buildings, in order to preserve and limit the degradations of the original facades.

2) Structural retrofitting works have no significant influence on the hygrothermal behaviour of old masonries.

3) Some of the thermal improving solutions may lead, during the winter, to condensation inside the outer masonry walls, if particular care is not given to the problem of vapour diffusion. This can lead to many damage patterns such as mould growth, migration and crystallisation of soluble salts, decay of wood elements, corrosion of steel elements and exposes the material to freeze-thaw cycles.

4) Using cellular expanded polystyrene as added thermal insulation on the inside of the wall leads to condensation in the building enclosure element during the winter.

5) The strengthening of masonry walls with reinforced concrete jacketing, followed by a thermal-insulation on the inside is a viable solution when using mineral wool and a vapour barrier. For this solution, the effective pressure of the vapours that enter into the enclosure element is very small, and condensation does not occur. Special measures must be taken to control ventilation and indoor air humidity.

6) The vapour barrier is extremely important and particular care must be given to its correct installation. When no vapour barrier is installed, a very high quantity of water accumulates in the wall during the cold season, which lowers the effectiveness of the thermal insulation. If in Bucharest and Iasi the wall dries

during the summer, in Braşov there is a net yearly water accumulation inside the wall.

A particular attention should be paid to the connection details between walls-floors and interior walls-outer walls, because the thermal bridges are more difficult to address when the thermal insulation layer is placed on the inside.

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## STUDIUL COMPORTĂRII HIGROTERMICE A CLĂDIRILOR ISTORICE CU STRUCTURĂ DIN ZIDĂRIE REABILITATE

(Rezumat)

Majoritatea clădirilor din România construite înainte de 1940 au structura din zidărie simplă. Aceste clădiri nu respectă cerinţele actuale privind siguranţa structurală şi izolarea termică şi necesită intervenţii în vederea reabilitării. Deoarece unele dintre aceste clădiri fac parte din patrimoniul arhitectural naţional, soluţiile de intervenţie trebuie să păstreze aspectul faţadei existente. Pereţii exteriori sunt în general consolidaţi prin dispunerea unei cămăşuieli armate şi, uneori, este prevăzut şi un sistem de izolare termică la interior. Sistemul de izolare termică dispus la interior poate determina acumularea de umiditate în interiorul peretelui, care poate conduce la degradarea acestuia. Articolul analizează comportarea higrotermică a pereţilor exteriori din zidărie simplă reabilitaţi. Sunt efectuale simulări numerice pentru configuraţiile tipice ale pereţilor clădirilor istorice şi pentru sistemele utilizate în mod curent în cadrul intervențiilor. Efectul izolației termice asupra acumulării de umiditate în interiorul pereților exteriori este analizat pentru trei orașe din România: București, Iași și Brașov. Sunt efectuate comparații cu reglementările naționale și europene în vigoare.