INCREASING THE ENERGY PERFORMANCE OF NON-RESIDENTIAL BUILDINGS BY THERMAL INSULATION OF WALLS ON THE INTERIOR SURFACE

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Abstract. Increasing the energy efficiency of buildings is one of the most important goals of today. In this context, the category of buildings with historical and architectural values is a special one, because the method consisting in adding an insulation layer on the outside is not an option, the only one is insulation on the inside of the walls. However, this solution does present certain risks of interstitial condensation and degradation due to frost or expansion of the masonry. The paper presents a study of a particular case of a building where only a façade cannot be thermally renovated from the outside because it has a mosaic surface. Thermal field simulations performed for a characteristic area emphasised the hygrothermal behaviour of the wall.

Keywords: interior insulation, thermal bridge, linear thermal transmittance, temperature factor, energy efficiency

1. Introduction

Sustainability and energy efficiency are key concepts of the present. According to the Buildings Performance Institute Europe [1], the buildings sector is responsible for 40% of total energy consumption and 36% of Greenhouse Gas Emissions (GHG). However, statistics show that about 35% of buildings are older than 50 years and 75% of the building stock is energy inefficient. Estimates suggest that there is potential for reducing the EU's overall energy consumption by 5-6% through measures to improve the energy efficiency of buildings and a corresponding reduction in total GHG emissions of around 5% [2].

In Romania, it is estimated that the stock of public buildings represents about 25% of the total number of buildings [3]. However, many of them (education, health, public administration) are very old, about 60% were built between 1950 and 1990. In addition, they have low thermal insulation, according to the standards of the time when they were built, and in many cases the thermal insulation is damaged due to climatic conditions. Several public buildings have a special status due to their historical value and architectural appearance, as many of them constitute the identity
of the city. This category of buildings requires special types of measures to increase energy efficiency. Usually these are measures to insulate building envelope elements, to increase the tightness, to replace glazing surfaces and to improve building equipment. However, in the case of this particular type of building, retrofitting is a complex act of intervention that poses particular challenges.

The category of buildings of architectural value is a special one, as they require special approaches, the essential element being the need to preserve the appearance of the façades. This is the case for old buildings (education, health, culture, commerce, tourism), many of which having brick structures (Figure 1), but also for some public buildings from the 1980s, with a monumental appearance, peculiar solutions for façade finishing that give the buildings their individuality (Figure 2).

![National College from Jassy](image1)

Fig. 1 – National College from Jassy
a. Main façade; b. Architectural details

!["Luceafărul" Theater for children and youth from Jassy](image2)

Fig. 2 – “Luceafărul” Theater for children and youth from Jassy
a. Main façade; b. Architectural details
Heat losses through the external walls account for the largest share of the overall energy balance of a building, namely 35% for ground floor buildings and 65% for multi-storey buildings. This justifies the constant effort to improve systems and solutions to ensure adequate thermal insulation for the opaque part of the façades, both in new buildings and in buildings undergoing renovation. The solution adopted in Romania after 1990 was to apply a layer of thermal insulation on the external surface of the wall, a layer protected with a thin plaster - ETICS system - or with a waterproof covering over a layer of air in contact with the outside air - Double-Skin system (ventilated façade). The solution is recommended first of all by adequate hygrothermal behaviour, as it eliminates the risk of progressive accumulation of condensed water vapour inside the structure, but also by other characteristics related to thermal inertia, simple technology, etc.

The extension of thermal energy rehabilitation action in the area of public buildings whose façades must be preserved, as well as the tendency to carry out partial thermal retrofitting works at the level of an apartment (which significantly affects the appearance of the façades), have drawn the attention of the parties involved to the solution of increasing the level of thermal insulation by applying an additional layer of thermal insulation material on the inner surface of the walls. This solution has a number of advantages, but it also involves certain risks that must be analysed in detail in order to avoid further negative consequences that are more difficult to resolve.

Moreover, in the case of buildings to be rehabilitated in this way, the assessment of energy performance requires knowledge of the value of the linear heat transfer coefficients corresponding to the solution of thermal insulation on the internal surface, different from those contained in the thermal bridge catalogues, which refer only to the situation of external thermal insulation.

2. Specificity of additional thermal insulation on inside part of walls

2.1. Exterior versus interior thermal insulation

In the retrofitting process, the reduction of transmission losses through walls plays an important role, as this element makes up a large part of the building envelope. There are two approaches to increasing the thermal insulation level of walls: on the outside and on the inside. The first solution is by far the most efficient (Figure 3).

However, for buildings of historical value or with façades that must be preserved, additional insulation on the inside remain the only option.
Fig. 3 – Comparison between exterior and interior thermal insulation

2.2 Risks associated with the additional insulation applied on the interior side of the building envelope elements

The thermal insulation on the inside can cause various hygrothermal and mechanical phenomena that affect the durability of existing walls. These are the alteration of the hygrothermal properties of the wall, and as a consequence, certain risks of interstitial condensation, frost damage, mould growth and other damage can occur. Today, however, there are some innovative systems that reduce moisture retention in the wall structure, but allow internal drying [4]. There are three types of insulation materials that are specifically suited for interior applications: capillary-active and vapour-open insulation materials that have the ability to buffer moisture, vapour-open insulation
materials that allow vapour to be transported into the wall, and vapour-tight systems that prevent moisture transport through the insulation [5].

The main risks that have been identified are:
- interstitial condensation by diffusion;
- degradation due to frost or expansion of masonry;
- decrease of thermal inertia and risk of overheating.

A detailed analysis of these risks allows the identification of the aspects that must be taken into account in choosing the optimal strategies in order to avoid them.

**a. The risk of interstitial condensation due to vapour diffusion**

Vapour condensation occurs when the actual pressure reaches the saturation value. In case of application of the thermal insulation layer on the inside, this phenomenon most likely occurs on the cold surface of the thermal insulation or on the interface between the thermal insulation and the existing structure. Moisture accumulated in the materials in this way can cause their degradation and, in particular, a significant decrease in the insulating capacity of the material.

**b. Freezing and deformability of masonry walls**

The fact that the wall structure is generally colder and wetter causes the penetration of the moisture front inwards, causing degradation, especially when freezing-thaw phenomena are associated, which increase/reduce the volume of water contained in the pores of the masonry blocks.

Therefore, the application of thermal insulation on the inside of the elements of the building envelope may aggravate an existing situation if no measures are taken to limit rainwater ingress and to maintain the drying potential of the wall. A waterproof cladding that closes off a layer of ventilated air could be a solution to reduce the negative effects mentioned above.

**3. Case study**

A particular case of an educational building was chosen as case study. The building has four floors and an amphitheatre at the upper level. Its bearing structure is made of reinforced concrete diaphragm walls with pillars in the façades plans. The building belongs to the Technical University “Gheorghe Asachi” from Iaşi, has been built in 1973, and in 2007 has undergone thermal rehabilitation in order to ensure the requirements of energy efficiency and indoor comfort. The applied thermal rehabilitation measures were: adding a 5 cm layer of expanded polystyrene on the external face of the envelope walls, 10 cm of extruded polystyrene on the roof and top amphitheatre floor and changing the old wooden windows with new ones of aluminium frames and insulated glazing. A particular element of this building is the presence of a mosaic on a part of the northern façade, which make impossible the
application of external insulation system (Figure 4). It is a special situation when the external insulation must be coupled with the interior one.

Fig. 4 – Building northern façade and mosaic detail

The constructive details of the external walls are presented in Figure 5, both for the wall without mosaic and the wall with mosaic.

Fig. 5 – External wall details: 1- internal plaster; 2 – reinforced concrete; 3 – unventilated air layer; 4 - masonry units with vertical holes; 5 – cement mortar; 6 – marble mosaic; 7 - expanded polystyrene (EPS) insulation; 8 – external plaster

The external corner between the wall without mosaic and the wall with mosaic will be further analysed in detail in terms of energy efficiency and surface condensation risk.
3.1. Method

The thermal field in this building zone was numerically modelled using the THERM 7.6 software [6], developed at Lawrence Berkeley National Laboratory (LBNL). Based on the finite-element method, THERM allows for two-dimensional conduction and radiation heat-transfer analysis in building components. The input data are the geometric and thermal characteristics of material layers, and boundary conditions. The results can be viewed as U-factors (R-values), heat flows, isotherms, flux vectors, constant flux lines, temperature values, and surface condensation potential.

The material properties used in simulation are presented in Table 1.

| No. | Material                                      | Thickness [cm] | Density [kg/m³] | Thermal conductivity [W/(mK)] |
|-----|-----------------------------------------------|----------------|-----------------|------------------------------|
| 1   | Lime-cement interior plaster                  | 2              | 1,700           | 0.87                         |
| 2   | Reinforced concrete                           | 20             | 2,500           | 1.74                         |
| 3   | Air layer (R = 0.18 m²K/W)                    | 6              | -               | -                            |
| 4   | Masonry units with vertical holes             | 14             | 1,450           | 0.64                         |
| 5   | Cement mortar                                 | 2              | 1,800           | 0.93                         |
| 6   | Mosaic                                        | 2              | 2,400           | 2.03                         |
| 7   | EPS insulation                                | 5              | 20              | 0.04                         |
| 8   | Exterior plaster                              | 0.7            | 1,750           | 0.90                         |
| 9   | Plasterboard                                  | 1.3            | 700             | 0.23                         |

The boundary conditions are: indoor air temperature $\theta_i = 20^\circ$C, interior surface heat transfer coefficient $h_i = 8$ W/m²K, outdoor air temperature $\theta_e = -15^\circ$C, exterior surface heat transfer coefficient $h_e = 24$ W/m²K. The relative humidity of the indoor air is $\text{RH}_i = 60\%$ and the relative humidity of the outdoor air for winter conditions is $\text{RH}_e = 85\%$.

By thermal field modelling with THERM, the influence of thermal bridging can be studied and the construction details can be optimized.

The influence of linear thermal bridges is taken into account by using linear thermal transmittances values, $\psi$ [W/(mK)], which can be found in thermal bridge atlases, i.e. the Romanian C107-3 P1-P6 [7] for the typical thermal bridges or must be determined using numerical calculation software.

The equation for $\psi$-value calculation is:

$$\psi = \frac{\Phi}{\Delta\theta} - \frac{B}{R} = U_{\text{therm}} \cdot l_{\text{therm}} - \frac{B}{R} \quad (1)$$

where: $\Phi$ is the thermal flow resulted from 2D numerical calculation for a surface having the width $B$ and the length 1 m, [W/m];
Δθ = θ_i - θ_e is the temperature difference between the indoor and outdoor environment, [K];

U_{therm} is the thermal transmittance calculated by THERM for area (length) corresponding to the thermal bridge, [W/(m²K)];

l_{therm} is the length of the contour of the heat transfer surface, [m];

B is the length corresponding to the thermal bridge, measured on the inner face of the exterior construction elements, in accordance with C107-2005, Part 3, Annex J, [m];

R is the thermal resistance of the construction element without thermal bridge (in current field), [m²K/W].

According to [8], it was introduced a criterion, the surface temperature factor, \( f_{Rsi} \), that is defined as the difference between the temperature on inner surface \( θ_{si} \), calculated with a surface resistance \( R_{si} \) and outside air temperature \( θ_e \), relative to the difference between the indoor air temperature \( θ_i \) and the outside air temperature \( θ_e \), and is expressed by the relation:

\[
f_{Rsi} = \frac{θ_{si} - θ_e}{θ_i - θ_e} = \frac{R - R_{si}}{R}
\]  

This parameter, which can also be defined as an indicator of the level of thermal insulation, can be calculated at any point of the building envelope, including the thermal bridge zones. Minimum values of the temperature factor, \( f_{Rsi,crit} \), were established and are specified in national regulation as design factors in order to avoid the mould growth risk or surface condensation risk.

For Romania, critical values of the temperature factor \( f_{Rsi} \) are given in [7], depending on the relative humidity of the indoor air and outdoor air temperature. For example, for \( θ_i = 20 °C, θ_e = -15 °C \) and \( RH_i = 60% \), the surface temperature factor \( f_{Rsi} \geq 0.78 \) to avoid the superficial condensation risk. The temperature factor \( f_{0.25} \) is calculated with a value of the interior surface thermal resistance \( R_{si} = 0.25 \text{ m}^2\text{K}/\text{W} \).

### 3.2. Results and Discussion

The thermal field was numerically modelled for the thermal bridge resulted at the external corner between the mosaic external wall and the regular external wall, which can be thermal insulated on the exterior surface.

To evaluate the thermal behaviour of this building area, 19 different configurations obtained by varying the thicknesses of thermal insulation layers have been studied, as presented in Table 2, in which:

- \( d_1 \) – thickness of the EPS layer applied on the exterior surface of the regular wall;
- $d_2$ – thickness of the EPS layer applied on the interior side of the mosaic wall and protected with a plasterboard of 1.3 cm thickness;

- $d_3$ – extension length of the EPS layer on the adjacent wall in order to minimise the thermal bridge effect.

### Table 2
Values of linear thermal transmittances and surface temperature factors for the analysed thermal bridges configurations

| Case No. | Thermal bridge configuration | Thermal bridge coefficient, $\psi$ [W/(mK)] | Temperature factor, $f$ [-] |
|----------|----------------------------|---------------------------------------------|-----------------------------|
|          | $d_1$ [cm] | $d_2$ [cm] | $d_3$ [cm] | 1-regular wall | 2-mosaic wall | 1-regular wall | 2-mosaic wall |
| 1        | 0           | 0           | 0           | 0.300         | 0.305         | 0.592         | 0.595        |
| 2        | 0           | 5           | 0           | 0.375         | 0.054         | 0.571         | 0.866        |
| 3        | 0           | 5           | 50          | -0.192        | 0.04          | 0.714         | 0.870        |
| 4        | 5           | 0           | 0           | 0.454         | 0.212         | 0.777         | 0.615        |
| 5        | 5           | 5           | 0           | 0.539         | 0.023         | 0.753         | 0.873        |
| 6        | 5           | 5           | 10          | 0.490         | -0.032        | 0.776         | 0.878        |
| 7        | 5           | 5           | 20          | 0.405         | -0.026        | 0.794         | 0.876        |
| 8        | 5           | 5           | 30          | 0.337         | -0.021        | 0.809         | 0.875        |
| 9        | 5           | 5           | 40          | 0.279         | -0.017        | 0.821         | 0.874        |
| 10       | 5           | 5           | 50          | 0.230         | -0.015        | 0.832         | 0.874        |
| 11       | 10          | 0           | 0           | 0.507         | 0.197         | 0.815         | 0.618        |
| 12       | 10          | 5           | 0           | 0.591         | 0.018         | 0.790         | 0.874        |
| 13       | 10          | 5           | 50          | 0.325         | -0.019        | 0.858         | 0.875        |
| 14       | 15          | 0           | 0           | 0.532         | 0.191         | 0.831         | 0.619        |
| 15       | 15          | 5           | 0           | 0.615         | 0.016         | 0.807         | 0.874        |
| 16       | 15          | 5           | 50          | 0.367         | -0.020        | 0.869         | 0.875        |
| 17       | 20          | 0           | 0           | 0.547         | 0.187         | 0.840         | 0.620        |
| 18       | 20          | 5           | 0           | 0.629         | 0.014         | 0.816         | 0.874        |
| 19       | 20          | 5           | 50          | 0.391         | -0.021        | 0.876         | 0.875        |

For all studied alternatives, using the output data resulted from THERM, the following results have been determined:

- values of the linear thermal transmittances of the thermal bridge, $\psi_1$ for the regular wall, and $\psi_2$ for the mosaic wall;

- surface temperature factors $f_{0.25}$, $f_1$ for the regular wall, and $f_2$ for the mosaic wall;

Examples of the results obtained are given in Figure 6, in two cases:

a) exterior insulation of 5 cm thickness;
b) 5 cm exterior insulation and 5 cm interior insulation with 50 cm extension on the adjacent wall.

![Thermal field, flux magnitude, isotherms](image)

Fig. 6 – THERM results for cases a) and b): thermal field, flux magnitude, isotherms

As can be observed in Figure 6, the exterior insulation only diminish the thermal flow through the regular wall, but the superficial condensation may occur on the internal surface of the corner. Through applying interior thermal insulation with an extension on the adjacent wall, the superficial condensation risk is eliminated.

Even if a 5 cm thickness of exterior insulation ensured the minimum energy efficiency requirements at the time when the thermal rehabilitation of the building has been accomplished, in present these conditions became more demanding, this is the reason for this paper analysed the increasing of the exterior insulation thickness until 20 cm.

The $\psi$-values variation according to the thickness of the exterior thermal insulation is presented in Figure 7, for three cases.

It can be observed that $\psi_1$-value is increasing in all cases comparative with the value for the uninsulated wall, which means an increase of the thermal bridge effect for the regular wall, with 82.3% in case A, 67.6% in case B. Even in case C, when effort has been made to correct the thermal bridging by extending the thermal insulation layer on the adjacent wall, $\psi_{1-C} = 0.391$ W/mK for 20 cm thickness of exterior insulation layer, which means an important thermal bridge effect. Contrary, the thermal bridge effect
for the mosaic wall ($\psi_2$-values) is decreasing with the increase of the thickness of the exterior thermal insulation layer.

For the same cases, in Figure 8 is presented the surface temperature factors variation, in comparison with the critical value, $f_{\text{crit}} = 0.78$. 

**Fig. 7 – $\psi$ coefficients variation according to the thermal insulation alternative.**
Case A – mosaic wall without interior thermal insulation; Case B – mosaic wall with 5 cm interior thermal insulation; Case C – mosaic wall with 5 cm interior insulation extended 50 cm on the adjacent wall.

**Fig. 8 – Temperature factors variation according to the thermal insulation alternative.**
Case A – mosaic wall without interior thermal insulation; Case B – mosaic wall with 5 cm interior thermal insulation; Case C – mosaic wall with 5 cm interior insulation extended 50 cm on the adjacent wall.
Regarding the surface temperature factors variation presented in Figure 8, it can be observed that, for the exterior thermal insulation layer thicker than 10 cm, all temperature factors have values greater than the critical value ($f_{\text{crit}} = 0.78$), except for the $f_{2-A}$ values, which assess the surface condensation risk on the uninsulated mosaic wall. It is found that an increase in the thickness of the external thermal insulation over the value of 10 cm does not significantly affect the value of the linear thermal transmittance nor of the temperature factor.

In Figure 9, the $\psi$ coefficients variation according to the length of the thermal insulation extension on the adjacent wall is presented, for 5 cm thickness of the thermal insulation layer, both on the exterior of the regular wall and the interior of the mosaic wall.

![Fig. 9 – $\psi$ coefficients variation according to the length of thermal insulation](image)

Regarding the variation of $\psi$-values with the length of thermal insulation extension, it is obvious that the thermal bridge effect is decreasing with the increase of the length, but the decision about the length value should also take into consideration economic and technological considerations.

### 4. Conclusions

In order to increase the thermal energy efficiency of buildings with historical or architectural values, the method consisting in applying an insulation layer on the outside of the walls is not a suitable solution.

The application of an insulation layer on the inside contributes significantly to the reduction of energy consumption, but carries some risks regarding interstitial condensation and degradation due to frost or expansion of the masonry.
The case study refers to a particular situation, respectively the case of a building where only one façade cannot be thermal rehabilitated from outside.

Thermal field simulations performed for a characteristic area (the jointing between the insulated wall on the outside and another one on the interior) revealed the following:
- applying the interior insulation leads to a decrease in linear thermal transmittance of this wall and an increase for the wall with exterior thermal insulation;
- increasing the thickness of the exterior thermal insulation layer over 10 cm does not significantly influence the value of linear thermal transmittance, and therefore nor the thermal bridging effect on the heat losses;
- the risk of surface condensation is present when the mosaic wall is not insulated and decreases with the application of the insulation, disappearing at 40 cm extending on the adjacent wall.

The analysis of the other thermal bridges presents in the Northern façade of the building (that with mosaic) as well as the risks associated with the proposed interior insulation will be the subject of a study, which besides stationary temperature field simulations, will also include simulations of the humidity regime and in situ measurements.

Based on this study, it will be possible to adopt the optimal system of thermal interior insulation, which will ensure a balance between the value of energy saved and the risks related to the hygrothermal behaviour and the depth of frost penetration.

REFERENCES
[1] F. Bean & all, *A guide to implement the energy performance of buildings directive (2018/844)*, Buildings Performance Institute Europe (BPIE), 2019.
[2] R. Dudău, *Creșterea eficienței eneregetice în clădiri în România: provocări, oportunități și recomandări de politici*, Energy Policy Group, 2018.
[3] Romanian National Institute of Statistics, https://insse.ro/cms/en.
[4] E. Vereecken, L. Van Gelder, H. Janssen, S. Roels, “*Interior insulation for wall retrofitting – A probabilistic analysis of energy savings and hygrothermal risks*”, Energy and Buildings 89 (2015) 231–244.
[5] T.K. Heusen, S.P. Bjarlov, R.H. Peuhkuri, M. Harrestrup, “*Long term in situ measurements of hygrothermal conditions at critical points in four cases of internally insulated historic solid masonry walls*”, Energy & Buildings 172 (2018) 235–248.
[6] Two-Dimensional Building Heat-Transfer Modeling THERM version 7.6, Lawrence Berkeley National Laboratory, https://windows.lbl.gov/software/therm.
[7] Catalogue with thermal bridges specific to buildings, C107-3 P1-P6, 2012 (in Romanian).
[8] *Hygrothermal performance of building components and building elements - Internal surface temperature to avoid critical surface humidity and interstitial condensation - Calculation methods*, SR EN ISO 13788, 2013 (in Romanian).