Numerical modelling of point thermal bridge’s impact on the thermal performance of facade systems

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Abstract. Starting with 31 December 2020 all new buildings, as well as existing ones, must comply with the nearly Zero Energy Buildings levels, as defined by each member state. A very important design criteria is the one regarding an accurate assessment of both linear and point thermal bridges of the building envelope. Usually, point thermal bridges are either not considered in calculations or are assessed by using simplified methodology as described by the standard EN ISO 6946/2017. This is due to the modelling and calculation complexity required in assessing them. Therefore, in several situations the impact is underestimated, and the thermal performance results do not offer a clear image of the building’s thermal performance. Thus, the paper focuses on the modelling and simulation of several constructive solutions for façade systems, aiming to identify a correlation between the geometrical and thermal characteristics of fixing components and the thermal performance of the façade. The studied case scenarios include two types of masonry walls, of 240 and 365 mm, that are thermally insulated in various thicknesses using an ETICS system. A sensitivity analysis is also performed to define a correlation between all the components that define the system and the point thermal bridge impact magnitude. The results of the study indicate an increased impact with a direct consequence on the energy performance of the building.

1. Introduction

The European Directive for the energy performance of buildings [1] gives the definition of a high performing energy efficient building, as being a nearly Zero Energy Building (nZEB). Two deadlines were set, one by 31 December 2018 and the second one for 31 December 2021, that mandates that all new buildings must reach nZEB levels in all European Union (EU) member states. Nevertheless, all member states had to define the nZEB levels than can be achieved at a national level, at optimum costs. A significant parameter in reaching nZEB levels is the reduction of the heat losses through thermal bridges. Depending on the constructive solution and the complexity of the architecture, these can count to about 30% or even more as mentioned by [2-3]. Several studies showed that a proper correction of the thermal bridges should result in a reduction of the energy consumptions for heating of at least 8.5%, that varying according to the climate type. [4]

In designing high performing energy efficient buildings, practitioners must carefully consider and assess the weak thermal areas in the structure of the building envelope. The weak thermal areas are known as thermal bridges and can be identified in the next cases, as given by the national thermotechnical design norm C107 [5]:

- when a material with a higher thermal conductivity $\lambda$ [W m$^{-1}$ K$^{-1}$], partially or fully penetrates a building envelope element (i.e. reinforced concrete column in a masonry wall);
- change in the thickness of the building envelope component.
- when differences exist between internal and external surfaces (i.e. intersection intermediate floor – exterior wall).

Therefore, thermal bridges can be point thermal bridges, linear thermal bridges, or spatial due to a spatial detail that defines such a weak thermal area. When calculating the thermal transmittance of building envelope components $U$ [W m$^{-2}$ K$^{-1}$], designers take into calculation only the value of the linear heat transfer coefficient denoted by $\psi$ [W m$^{-1}$ K$^{-1}$] (i.e. quantifies the magnitude of a linear
thermal bridge), while the point heat transfer coefficient denoted by $\chi$ [W K$^{-1}$] (i.e. quantifies the magnitude of a point thermal bridge), in many cases, is not considered in calculations.

Practitioners use atlases of thermal bridges [6,7,8] or the European standard [9] that gives 76 cases for thermal bridges details, as e.g. exterior corners, interior corners, intersection between slab on the ground and exterior walls, floors above unheated basements, attic roofs, roofs, intermediate floors – exterior walls intersection, window/door-wall intersection, balcony slabs-exterior walls, exterior wall with a column, and others. Designers can also address thermal bridges through modelling and simulation, but this requires knowledge which often lacks, and significant time for a proper simulation of the examined thermal bridge. Therefore, usage of thermal bridges atlases is the first choice in obtaining design values. The thermal bridges atlases offer design values for the $\psi$ value, and not for the $\chi$. On the same time, obtaining $\chi$ values requires advanced knowledge in modelling and simulation and a specific software for this aim. Due to that, the $\chi$ values are either not found in calculations or assessed using a simplified methodology defined in [10], although that for ventilated facades the point bridges can have a more significant impact on the thermal performance level compared the one assessed through a simplified approach. The scientific literature offers several studies in evaluating the negative impact of metal fasteners mainly for the case of ventilated facades or facades with integrated photovoltaics as mentioned by Theodosiou [11-12], curtain walls [13] or light steel frame structures [14].

Point thermal bridges are caused by fasteners (i.e. anchors, bolts, brackets and other similar components) that are needed for fixing the thermal insulation system or and the ventilated façade system, or other types of systems to the support layer. The point thermal bridges can have a significant influence in establishing the real thermal performance of a building component, with a reach of 20% or higher, and implicitly with a same impact on the energy performance of a building [11,12,14]. Even in the case of envelope elements thermally insulated with aerogel blankets that are penetrated by metal anchors [15], the thermal resistance could decrease by 15% to 45% when using 3 to 6 anchors per m$^2$.

The aim of the paper consists in investigating the impact that the anchors, defined by their thermal properties and geometric dimensions, have on the thermal performance of the building envelope component. At the same time, the influence on the $\chi$ value due to the thermal insulation thickness and conductivity, number of anchors and type of support layer, are also assessed. Thermally insulated constructive details specific for External Thermal Insulation Composite Systems (ETICS) are modelled and simulated. Although that literature [12] mentioned that 3D thermal bridges (i.e. point thermal bridges) at ETICS can be considered as having a slightly less negative influence compared to other constructive solutions, the study will demonstrate that these should be considered in calculations.

2. Materials and methods

2.1. Parameters of ETICS and support layer

A typical ETICS system is defined by the following components: adhesive, thermal insulation material, anchors, base coat, reinforcement (i.e. usually glass fibre mesh) and a finishing layer: (i.e. finishing coat with a key coat and/or a decorative coat) and various accessories.[16] The anchors have the role of mechanically fixing the thermal insulation layer to the support layer (e.g. masonry, concrete). Anchors have a higher thermal conductivity $\lambda$ [W m$^{-1}$ K$^{-1}$] compared to the thermal insulating layer, thus conducting heat at a higher rate. Thus, the anchors become point thermal bridges in the structure of the building envelope due to their weak thermal performance.

The paper investigated the case for a support layer defined by a full brick masonry with $\lambda =0.80$ [W m$^{-1}$ K$^{-1}$], in two situations, a 24 cm support layer, and a 36.5 cm layer. For the thermal insulating systems, the study gives the results for thicknesses starting from 50 mm up to 300 mm. Four situations for the number of used anchors, starting from 6 up to 12 anchors per m$^2$, were analysed. The length of the anchors, the radius of the anchors cap and the distance between the anchors was defined in accordance with ETICS standard [17]. The thermal conductivity for the thermal insulation was 0.040 [W m$^{-1}$ K$^{-1}$] and 50 [W m$^{-1}$ K$^{-1}$] for the steel anchors. The thermal insulation layer was chosen with an
average value, without referring to a specific type.

| Parameter                          | Range examined      |
|------------------------------------|---------------------|
| Support layer (SL)                 | masonry             |
| Thickness SL                       | 240, 365 [mm]       |
| Thermal conductivity SL            | 0.80 [W m\(^{-1}\) K\(^{-1}\)] |
| Anchor type (A)                    | Steel               |
| Thermal conductivity A             | 50 [W m\(^{-1}\) K\(^{-1}\)] |
| Number of A                        | 6, 8, 10, 12 /m\(^2\) |
| Thermal insulation (Tins) conductivity | 0.04 [W m\(^{-1}\) K\(^{-1}\)] |
| Tins thickness (D\(_{ins}\))       | 50, 100, 150, 200, 250, 300 [mm] |

Figure 1. Anchor placement - T pattern diagram

2.2. The modelling and simulation

The modelling and simulation of the point thermal bridges implies a 3D modelling approach for proper assessment of the heat losses, which is given by a higher complexity numerical approach compared to the case of linear thermal bridges. Therefore, the HISPAT 3D modelling and simulation software was used [18], which was developed by the authors of this paper.

The software knew three stages of national validation since its first development back in 1978:

- 1\(^{st}\) stage: a validation of the program in correlation with the experimental data obtained at INCERC Iasi;
- 2\(^{nd}\) stage: in the 90’s together with IPCT, the program was used for the development of the thermal bridges annexes of C107/3 norm. The program was validated in accordance with the stipulations of Annex A, EN ISO 10211/1995;
- 3\(^{rd}\) stage: when the Annex 1590, of the C107 Norm was developed, the program was again validated according to SR EN ISO 10211/2008.
today the program is validated according to SR EN ISO 10211/2017, Annex C. The software is based on solving the spatial heat transfer differential equation in steady state thermal regime without internal heat sources, where \( T \) is the temperature and \( \lambda_x, \lambda_y, \lambda_z \) is the thermal conductivities of the material on \( x, y, z \) direction.

\[
\frac{\partial}{\partial x} \left( \lambda_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda_z \frac{\partial T}{\partial z} \right) = 0
\]  

(1)

The mesh is generated by the software following a grid dimension suitable for the studied case. The boundary conditions respect the European prescriptions [10]. The mesh is typical for metallic thermal bridges. The boundary conditions are \( R_{si}=0.13 \text{ m}^2\text{K.W}^{-1} \) and \( R_{se}=0.04 \text{ m}^2\text{K.W}^{-1} \), while the temperature difference has a unitary value according to Annex E of [10].

The discretisation steps start from 1mm up to 25 mm, with an increased density in the anchor’s mesh. The distribution of the temperature field is calculated through an iterative process, that ends when the convergence criteria given by the difference between inner and outer heat flow is smaller than 0.001 W and heat flow between two consecutive iterations is smaller than 0.000001 W.

To determine the influence of the anchors on the wall’s thermal transmittance, the case scenarios were considered with and without the anchors. First, the 3D modelling and simulation was done with the 3D HISPAT software for the first case scenario, and a 1D calculation was done for the latter case. The value of the difference between the two heat flows indicates the amount of heat flow through the point thermal bridge. The formula for calculating \( \chi \) was used according to [10]:

\[
\chi = L_{3D} - U \cdot V
\]  

(2)

where \( L_{3D} [\text{W.K}^{-1}] \) is the thermal coupling coefficient calculated by a 3D approach, the \( U [\text{W.m}^{-2}\text{K}^{-1}] \) is the thermal transmittance and \( A [\text{m}^2] \) is the area of the examined building element.

The changes in the examined detail for each case scenario is followed by a new redefined mesh, in order to ensure the accuracy in calculation. As it can be observed in figure 2 at the anchors mesh, when the geometry of the element is more complex, the density of the mesh will increase.

3. Results and discussions

The research was made for different types of support layers, starting from full brick masonry, reinforced concrete, aerated cellular concrete. However, the paper will present the results for the masonry case. Results are summarised for the case scenarios mentioned in table 1, the unidirectional thermal resistance \( R \) and the adjusted thermal resistance \( R' [\text{m}^2\text{K.W}^{-1}] \) are pointed out as main indicators. \( R \) was calculated in accordance with the layers that defined the analysed constructive details. The temperature field distribution is presented in figure 3, for one of the studied cases.
As it can be observed, the steel anchor is causing a disturbance in the temperature curves distribution and implicitly a weaker thermal point, which leads to a decreased thermal performance.

3.1. Impact of the number of anchors
The results are given starting from the case with 50 mm to 300 mm of thermal insulation for both case scenario, i.e. full brick masonry 240 mm – case scenario 1 (CS1) and full brick masonry 365 mm – case scenario 2 (CS2). The simulations were made with steps of 1 cm for thermal insulation thickness (i.e. 26 variants), but for a clean presentation the scale only indicates the six thicknesses values, from 50 to 300 mm.

As it can be observed in figure 4 and figure 5, $\chi$ has a greater value, and implicitly impact, in the case of a thinner masonry compared to a thicker one. For CS1 the values range from the lowest value of 0,012 [W K$^{-1}$] for the case of 6 anchors/m$^2$ and 300 mm Tins to an almost 0.043 [W K$^{-1}$] for the case of 12 anchors/m$^2$ and 70 mm Tins.
For CS2 the values range from the lowest value of 0.010 [W K$^{-1}$] for the case of 6 anchors/m$^2$ and 300 mm Tins to an almost 0.036 [W K$^{-1}$] for the case of 12 anchors/m$^2$ and 70 mm Tins. At the same time, one can see that the step for the variation of $\chi$ increases with the increase of the anchors number but decreases with the increase of the support layer thickness.

3.2. The impact of the anchor’s length

For CS1, the growth for the $R$ value starts by a 41% and ends with a 78% compared with the reference case, the one for 50 mm. For CS2, the growth is smaller, starting from a 39% to a 76%. Furthermore, both $R$ and $R'$ are smaller compared to the reference value for exterior walls $R_{\text{min}}=1.80$ [m$^2$ K W$^{-1}$] [19] in the case of C1. For CS2, all $R$ and $R'$ values are greater than the $R_{\text{min}}$ reference value.

In the light of the NZEB criteria, the proposed $R'$ values will be for residential buildings $R'_{\text{min}}=4.00$ [m$^2$ K W$^{-1}$] and for non-residential buildings $R'_{\text{min}}=3.00$ [m$^2$ K W$^{-1}$] [20]. Thus, for CS1 the values will not be met for residential buildings for cases 50 mm to 150 mm, respectively for non-residential buildings for cases 50 to 100 mm Tins. For CS2 the values will not be met for residential buildings for cases 50 mm to 100 mm Tins, respectively for the 150 mm Tins, 10 to 12 anchors/m$^2$ cases. In case of non-residential buildings, the values will not be met for 50- and 100-mm Tins, especially 8 to 12 anchors/m$^2$ case scenarios.
Figure 5. The $\chi$ value – full brick masonry 365 mm

Table 2. The adjusted thermal resistance - no of anchors - masonry 240 mm

| $D_{\text{ms}}$ [mm] | $R$ [$m^2 \cdot K/W$] | $R'$ [$m^2 \cdot K/W$] | Number of anchors |
|---------------------|---------------------|---------------------|------------------|
| 50                  | 1.776               | 1.711               | 1.691            | 1.671 | 1.652 |
| 100                 | 3.026               | 2.847               | 2.792            | 2.740 | 2.689 |
| 150                 | 4.276               | 3.967               | 3.873            | 3.784 | 3.699 |
| 200                 | 5.526               | 5.080               | 4.947            | 4.820 | 4.700 |
| 250                 | 6.776               | 6.190               | 6.017            | 5.853 | 5.698 |
| 300                 | 8.026               | 7.300               | 7.087            | 6.886 | 6.695 |

Regarding the reduction of $R'$ value with respect to the number of anchors and the $R$ value, the reduction percentage increases with the increase of the thermal insulation layer, starting form 4% (i.e. for 6 anchors/m², 50 mm Tins) to 17% (i.e. for 12 anchors/m², 300 mm Tins) for CS1 and 3% (i.e. for 6 anchors/m², 50 mm Tins) to 16% (i.e. for 12 anchors/m², 300 mm Tins) for CS2. The increased percentage value could be also associated to a longer dimension of the steel anchors.
Table 3. The adjusted thermal resistance - no of anchors - masonry

| D_{ms} [mm] | R [m^2·K/W] | R' [m^2·K/W] | Number of anchors |
|-------------|-------------|--------------|------------------|
|             |             |              | 6    | 8    | 10   | 12   |
| 50          | 1.931       | 1.864        | 1.847 | 1.827 | 1.807 |
| 100         | 3.182       | 3.003        | 2.947 | 2.893 | 2.842 |
| 150         | 4.432       | 4.122        | 4.029 | 3.939 | 3.853 |
| 200         | 5.682       | 5.238        | 5.105 | 4.978 | 4.858 |
| 250         | 6.932       | 6.345        | 6.170 | 6.005 | 5.849 |
| 300         | 8.182       | 7.452        | 7.237 | 7.033 | 6.841 |

The obtained results are consistent with results from reference papers [11,12]. As it can be observed in [12], the effect of the thermal insulation on the $\chi$ value is given with a similar allure, with a clear spike in between 50 – 100 mm of thermal insulation. Sadauskiene in [21] obtained continuous reductions of $\chi$ values for increased thickness of the SL, similar to the findings presented in figures 4 and 5.

3.3. The impact of the anchor on the thermal performance and energy consumption

In order to assess the impact that the anchors have on the overall thermal performance of a building, the case of a residential building is considered. The building is in Cluj-Napoca, location defined by the IIIrd climatic zone and an exterior temperature $\theta_e$=-18°C. The height regime is basement partially heated+ground floor + 1st floor. The heated useful area is 166 m$^2$ and the area of the building envelope is 435 m$^2$. In table 4 are presented the R’ values for a part of the building envelope components.
Table 4. $R'$ for the building envelope elements (extract) [m$^2$K W$^{-1}$]

| Element                      | $R'$ |
|------------------------------|------|
| Exterior wall                | 5.29 |
| Exterior glazing             | 1.10 |
| Attic roof                   | 5.48 |
| Floor in contact with the ground | 6.37 |

The assessed thermal bridges were just the linear ones, without addressing the point thermal bridges. The final energy consumption for heating resulted in a value $q_{heating}=67.38$ [kWh/m$^2$.yr], which means an A energy class for heating, based on the national legislation which requires a value $\leq 70$ [kWh/m$^2$.yr]. By including the effect of the point thermal bridges the $q_{heating}$ will rise up to a value of 74.49 [kWh/m$^2$.yr] which will lead to a B energy class for heating. Therefore, the impact of the anchors should be investigated to not underestimate the actual heat flows through the building’s façade.

4. Conclusions

The nZEB requirements come with a lot of pressure on both energy auditors for buildings and designers, mainly the one specialised in the thermal design of the building envelope. Nevertheless, reaching the required levels in design and operation, will be translated in a proper assessment of all type of thermal bridges.

In most cases, point thermal bridges are not considered in calculations due to their complexity and lack of knowledge regarding their simulation. Also, a general perception is that for single-skin façade, their input is not significant, although that the present papers demonstrates that not always this applies. The constructive details for nZEB must have increased thicknesses of the insulation layers which will translate in an increased impact of the anchor’s presence. The results obtained for the 240 mm and 365 mm full brick masonry walls, thermally insulated in various thicknesses, demonstrate the need of considering the impact of $\chi$ values. The magnitude of the point thermal bridges increases with an increased anchors length needed in case of high thermal insulations thicknesses, resulting in a $R'$ reduced of up to 17% compared to $R$ value.

For more complex details (i.e. ventilated façade), the heat flows associated with point thermal bridges can represent more than 25% from the total heat flows through the building envelope, as mentioned by literature. The results of the study can be used as input in design work, for similar cases with the ones investigated here.

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