Modelling of Edge Insulation Depending on Boundary Conditions for the Ground Level

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Abstract. The article presents results of CFD software aided simulations of a thermal bridge, existing at the wall–slab on ground connection. Calculations were made for different variants of the edge insulation location. Schemes without any edge insulation, with some vertical insulation, horizontal, diagonal, and diagonal combined with insulation used as formwork under the slab on ground were analysed. Each variant was differentiated with boundary conditions for the ground. Vertical borders of the model in the ground, as well as the lower border were described in the first solution as adiabatic, while in the second case, a variable temperature value, depending on the ground depth, was set. For comparison, additional calculations were conducted for non-stationary conditions, in which the initial temperature of the ground was set to the average annual temperature of air. The calculations were based on the location of Szczecin, for which the outside air temperature was set to -16.0°C. Results obtained from the simulation were then used to determine the thermal bridge parameters, in particular, thermal coupling coefficient and linear thermal transmittance. The effect of the set of boundary conditions is clearly seen. In general, for all the five variants, lower values of heat fluxes and linear thermal transmittances were obtained, when variable temperature in the ground was assumed. From the point of view of energy balance, it is more favourable to use the values of $\psi_g$ obtained when the ground temperature is taken into account. The data breakdown shows that application of the actual temperature distribution in the ground to a model has a strong effect on distribution of the 0.0°C isotherm. The adiabatic model indicates that the ground under the slab freezes, while the model, which takes into account the temperature of the ground, shows that the ground under the floor has positive temperatures and the 0.0°C isotherm reaches only the edge of the outer wall. Moreover, the effect of the adopted ground temperatures on the hygrothermal parameters of the cases in question was demonstrated. The models that take into account the temperature of the ground result in more favourable values than those in the adiabatic models. For non-stationary heat flow conditions, the advantages of the diagonal edge isolation, which caused significant offset of the zero isotherm from the foundations, were presented. Variants of horizontal and diagonal edge insulations eliminate the risk of freezing of the foundation and the ground beneath it.

1. Introduction

Due to the high thermal inertia of the soil, temperatures below the ground level are subjected to rather little fluctuations during the year, as in the summer the soil absorbs heat to give it away in the winter. Thanks to that, at levels below 5 meters, the ground keeps almost steady temperature of about 8°C. In the winter conditions, the soil temperature, which is higher than the external air temperature, may influence the technical parameters of connections between walls and slabs placed on the ground.
In particular, this is relevant to the linear thermal transmittance, used for calculation of heat loss of partitions. Therefore, taking the ground temperature into account helps to achieve higher precision in the calculations related to the energy balance of buildings.

Although calculations related to partition connections are conducted mostly using applicable catalogues of thermal bridges, nowadays more often simulation software supporting those calculations [1], [2] are in use. Among others, the ASIEPI [3] project supports the use of simulation instead of application of default values, obtained with simplified methods. Additionally, thermal bridges are more often tested in non-stationary heat flow conditions [4], [5], [6]. Therefore, the authors gathered results related to simulation of the thermal bridge that occurs at the wall–slab on ground connection, using the CFD software.

The calculations were conducted in two variants: based on standard [7], and based on the guidelines provided in [8]. For the calculations, a 2-D, geometric model of the wall–slab on ground connection was prepared in accordance with the rules set forth in standard [7]. According to them, all planes of the section should be the adiabatic boundaries (zero heat transfer). On the other hand, application of the method quoted for in standard [8] to the simulations helps to acquire information about monthly gains of energy from the ground, which enhances precision of the building energy calculations. The standard presents a method of calculation of ground temperature depending on the depth, type of soil, average annual external air temperature, maximum and minimum average monthly air temperature. The meteorological data for the locations in Poland that are necessary for the calculations are available at site [9]. Figure 1 shows the average temperature of the ground and the average monthly outdoor temperature for Szczecin.

![Figure 1. The average temperature of ground and monthly average outdoor temperature for Szczecin](image)

2. Materials and methods

In order to determine the impact of the ground temperature on the hygrothermal parameters, the external wall connection to the slab on the ground was analysed in several variants. For the assessment, five variants of the slab on the ground, with different edge insulation type, were adopted. Schemes of the variants in study are presented in figure 2. For the simulations, the following variants were used:

- variant 1 – no edge insulation,
- variant 2 – vertical edge insulation,
- variant 3 – horizontal edge insulation,
- variant 4 – diagonal edge insulation,
- variant 5 – diagonal edge insulation, combined with insulation being the permanent formwork under the slab.
Figure 2. Schemes of analysed variants of slab on ground edge insulation

The thermal transmittances $U$ for the partitions in question amounted respectively 0.197 W/m²·K for the external wall, 0.207 W/m²·K for the slab on the ground in variants 1÷4, and 0.165 W/m²·K for variant 5. For the edge insulation, in all the variants, 10 cm-thick expanded polystyrene XPS, with the thermal conductivity $\lambda$ equal to 0.04 W/m·K was proposed. Each variant was subjected to two types of stationary calculations in the CFD software. The calculations were differentiated with the ground boundary conditions. In the first scheme, adiabatic boundaries (A) were adopted, while secondly, the temperature in the ground was varied depending on the depth (Tg). For comparison, additional calculations for non-stationary conditions were performed.

The computational model was prepared in compliance with the rules set forth in standard [7]. The slab that was set for the calculations was formed on a rectangular plan, with total external dimensions of 10x14 m. The calculated characteristic dimension of the slab on ground $B'$ was 5.83 m [10]. It was assumed that under the slab there was the 2nd category ground, with the thermal conductivity coefficient $\lambda$ equal to 2.0 W/m·K. For all the variants, the same internal temperature $\theta_i$ of 20°C and external temperature $\theta_e$ of -16°C were set. External surface resistance was equal to 0.04 m²·K/W and internal surface resistances were set at 0.13 m²·K/W and 0.17 m²·K/W for internal surfaces. In order to determine the temperatures necessary for calculating the temperature factor, the internal surface resistance was increased up to 0.25 m²·W/K [11].

Results of the computer simulations were then used to determine the parameters of the thermal bridge [7], i.e. the thermal coupling coefficient $L_{2D}$ and the linear thermal transmittance $\psi$.

$$\Phi_l = L_{2D}(\theta_i - \theta_e) \quad (1)$$

where:
- $\Phi_l$ – heat flow per meter of length of the thermal bridge, from the internal environment $i$ to the external environment $e$, [W]
- $L_{2D}$ – linear thermal coupling coefficient [W/m·K], obtained from 2-D calculations of a component separating the two environments in study.
- $\psi = L_{2D} - \sum_{j=1}^{N} U_j l_j \quad (2)$
where:
\( \psi \) – linear thermal transmittance of the thermal bridge, separating the two environments in question, [W/m·K]
\( U_j \) – 1-D thermal transmittance coefficient of component \( j \), separating the two environments in question, [W/m²·K]
\( l_j \) – length within the 2-D geometric model, for which value \( U_j \) [m] is used,
N – number of 1-D components.

Values of the linear thermal transmittance coefficient for the wall-slab connection are determined, depending on the applied dimensions (internal \( i \), and external \( e \)), gained from the following formulas:

\[
\psi_{gi} = L_{2D} - h_w U_w - 0.5 B' U_g
\]

(3)

\[
\psi_{ge} = L_{2D} - (h_w + h_f) U_w - 0.5 (B' + w) U_g
\]

(4)

where:
\( U_w \) – thermal transmittance coefficient of a wall above the ground, [W/m²·K]
\( h_f \) – height of the slab above the ground level, [m]
\( h_w \) – minimum distance between the connection and the cross-section plane, [m].

Vertical boundaries of the model in the ground, as well as its lower boundary, were described in the first solution as adiabatic (A), while in the second case variable temperature (Tg), determined with equation (1) as per standard [8]. Figure 3 presents a graph reflecting the change of the temperature in the ground, depending on the depth. Ground temperature \( T_g \) was determined with the following formula:

\[
T_g = g m \left[ T_{AM} - A H \cdot \Delta T_A \cdot \sin \left( \frac{2 \pi}{8760} (JH - VS + 24 \cdot 25) \right) \right]
\]

(5)

where:
gm – ground material factor,
\( T_{AM} \) – annual mean outside temperature, [°C]
AH – amplitude correction factor,
\( \Delta T_A \) – amplitude of annual outside air temperature swing, [°C]
JH – annual hour,
VS – curve shift.

**Figure 3.** Temperature distribution in ground
The coefficients used in equation (5) are gained from formulas (6) and (7), where \( d \) represents the depth in [m].

\[
AH = -0.000335 \cdot d^3 + 0.01381 \cdot d^2 - 0.1993 \cdot d + 1 \quad (6)
\]

\[
VS = 24 \cdot (-0.0195 \cdot d^4 + 0.3385 \cdot d^3 - 1.0156 \cdot d^2 + 10.298 \cdot d + 0.1786) \quad (7)
\]

An exemplary temperature distribution for variant 2 in the two analysed stationary heat flow schemes is presented in figure 4.

![Temperature distribution](image)

**Figure 4.** Temperature distribution in ground for variant 2 with adiabatic boundary conditions (A), and conditions described with function of temperature in ground (Tg)

Non-stationary heat transfer conditions were also simulated. The initial temperature in the ground was set as equal to the average annual air temperature value, taken from the Szczecin-Dąbie meteorological station [9], being 8.8°C. The ground specific heat was adopted based on [8] and equal to 1200J/kg·K. The thermal conductivity coefficient of the ground was also set at 2.0W/m·K, similarly as in the stationary models. The ground boundary conditions were assumed as adiabatic. The air temperatures were left as those in the stationary calculations. It was tested how long the temperature of the ground under the slab took to drop below 0.0°C. Moreover, the temperature distributions in the ground in the axis of the external wall were analysed after simulations of 30 days of the heat transfer.

### 3. Results and discussions

Calculations performed for all the variants delivered the results gathered in table 1.

| Type     | Q [W] | L_2D [W/m·K] | \( \psi_g \) [W/m·K] | \( \psi_{ge} \) [W/m·K] |
|----------|-------|--------------|-----------------------|------------------------|
|          | A     | Tg           | A                     | Tg                     | \( \Delta \) [%] | A     | Tg | \( \Delta \) | A | Tg | \( \Delta \) |
| Variant 1| 79.33 | 69.84        | 2.20                  | 1.94                   | 11.95               | 0.96   | 0.70 | 0.26 | 0.81 | 0.54 | 0.26 |
| Variant 2| 63.33 | 53.08        | 1.76                  | 1.47                   | 16.18               | 0.52   | 0.23 | 0.28 | 0.36 | 0.08 | 0.28 |
| Variant 3| 62.71 | 52.13        | 1.74                  | 1.45                   | 16.87               | 0.50   | 0.21 | 0.29 | 0.35 | 0.05 | 0.29 |
| Variant 4| 59.33 | 48.74        | 1.65                  | 1.35                   | 17.85               | 0.41   | 0.11 | 0.29 | 0.25 | -0.04 | 0.29 |
| Variant 5| 43.68 | 35.39        | 1.21                  | 0.98                   | 18.98               | 0.19   | -0.04 | 0.23 | 0.05 | -0.41 | 0.23 |

The influence of the adopted boundary conditions is clearly seen. Generally, for all the five variants, lower values of the heat flow and the linear thermal transmittances were obtained, with the assumption...
that the boundary conditions of ground temperature varied depending on the depth. In the variants 3 and 4, the difference in value $\psi_g$ amounts to 0.29 W/m·K. The smallest differences appeared for variant 5, where the insulation was made as the permanent formwork, for which $\Delta$ was 0.23 W/m·K. This further translates to precision of calculation of the heat loss of the building. From the perspective of the energy balance, it is better to use the values of $\psi_g$ for the wall–slab on ground thermal bridge, determined with consideration given to the ground temperature.

Figure 5 presents the zero isotherms curves for some selected characteristic variants. The juxtaposition shows that adoption of the actual temperature distribution in the ground has a strong effect on distribution of the 0.0°C isotherms. For example, the adiabatic model (A) of variant 5 indicates that the whole ground under the slab freezes and the temperature 0.0°C occurs directly in the slab insulation. On the other hand, in model (Tg) the ground under the slab has a positive temperature nearly on its whole area, while the 0.0°C isotherm does not reach further than the external wall.

Figure 5. Zero isotherm of selected variants

In the places where thermal bridges exist, it is also important to study the problems related to moisture condensation. Table 2 presents a comparison of the dew point and temperature factor $f_{Rsi}$. Variant 5, with the highest temperature in the corner, comes up the most favourable. It needs to be noted that, again, in models (Tg) the obtained values are more favourable than those in the adiabatic models. The biggest differences in the results appear in variants 3 and 4.

Table 2. Comparison of hygrothermal parameters

| Type     | Temperature in corner [°C] | Boundary humidity that meets the requirements of dew point [%] | $f_{Rsi}$ [-] |
|----------|---------------------------|-----------------------------------------------------------------|--------------|
|          | A      | Tg     | $\Delta$ [%] | A      | Tg     | $\Delta$ [%] | A      | Tg     | $\Delta$ [%] |
| Variant 1 | 9.56   | 10.23  | 7.00         | 5.08   | 5.22   | 4.59         | 0.71   | 0.73   | 2.62         |
| Variant 2 | 12.20  | 13.14  | 7.68         | 6.06   | 6.50   | 6.33         | 0.78   | 0.81   | 3.32         |
| Variant 3 | 12.25  | 13.27  | 8.37         | 6.08   | 6.08   | 6.94         | 0.78   | 0.81   | 3.63         |
| Variant 4 | 12.68  | 13.76  | 8.46         | 6.21   | 6.15   | 7.25         | 0.80   | 0.83   | 3.74         |
| Variant 5 | 15.64  | 16.12  | 3.07         | 7.85   | 7.82   | 3.11         | 0.88   | 0.89   | 1.52         |

Additionally, tests with non-stationary heat flow were conducted. Figure 6 presents distribution of the 0.0°C isotherms after simulations of thirty days of heat transfer. The absence of edge insulation
in variant 1 resulted in freezing of the foundation and the underlying ground, whereas in the other cases such a risk does not occur. The best performance was observed in the variants with the diagonal insulation, which cause a significant shift of the zero isotherm from the foundation area.

![Image]

**Figure 6.** Zero isotherms of each variant after 30 days of non-stationary heat flow simulations

The scale of the impact of the applied edge insulation is presented in figure 7, where the minimum time necessary for cooling the ground under the foundation below 0.0°C is shown. Only for variant 1 there is a real risk that the ground under the slab will freeze. The other variants eliminate this risk entirely. The times obtained in the tests are many times longer than the actual duration of freezing temperatures in the winter season.

![Image]

**Figure 7.** The time required to cool down temperature of the ground under foundation below 0.0°C

The last figure 8 shows the temperature distribution along the external wall axis, from the slab level (0.0m) down to the depth of 2.0m in the ground. The highest temperatures were measured for variant 5, at depth of 0.0 m, while the lowest ones were observed in variant 1 – the one without the edge insulation. From level 0.4m down to 1.1m, variant 1 remains within the range of freezing temperatures. For the other variants, the graphs remain entirely in the plus temperature range. The smallest temperature drops were observed in the variants with the diagonal and horizontal insulation (variants 3, 4 and 5).
4. Conclusions

The paper presents results of calculations conducted with the CFD software, with the example of a thermal bridge of the wall–slab on ground connection. The influence of the adopted boundary conditions on parameters obtained in stationary and non-stationary calculations was analysed. A favourable influence of adopting the actual temperature distribution of the ground on values of linear thermal transmittance and total heat flow is clearly seen. Additionally, the graphs of the 0.0°C isotherms of which location depends directly on the adopted boundary conditions, were presented. It was proven that substituting the adiabatic boundary conditions with a function of the actual distribution of temperatures in the ground resulted in delivering graphs that better reflect actual conditions.

Application of the recommendations given in standard [7] resulted in obtaining such data that, with a significant safety margin, evaluate the possibility of condensation in the thermal bridge in question. Taking the temperature of the ground into account brings about an increase of the value of the temperature in the corner and of temperature factor $f_{Rsi}$ by a couple of percent.

The simulation of wall–slab on ground in conditions of non-stationary heat flow demonstrates the advantage of the use of diagonal isolation, which cause significant offset of zero isotherm from foundations perimeter. Variants 3, 4 and 5 eliminate entirely the risk that the foundation and the ground under it may freeze, at the adopted thermal conditions. The obtained cooling times are many times longer than the actual duration of freezing temperatures in the winter.

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