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Shaping material systems of contemporary external partition joints in terms of thermal and humidity requirements

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Abstract: The article presents the principles of shaping material systems of modern building joints in terms of thermal and humidity requirements. An integral part of the work is the calculation of the physical parameters of the connection between the external wall and the window using a computer program. The choice of material solutions for construction joints should be based on calculations and analyzes of their physical parameters. The physical parameters of the connection between the external wall and the window in the cross-section through the lintel depend on the arrangement of the material layers of the joint: e.g. type and thickness of thermal insulation, window location. Improper shaping of the arrangement of material layers results in increased heat losses in the form of heat flux Φ [W] and linear heat transfer coefficient Ψ [W/(m·K)] and a decrease in temperature on the internal surface of the partition at the thermal bridge, which may lead to the risk of the occurrence of condensation on the inner surface of the partition.

Keywords: construction joint, thermal and humidity requirements, shaping material systems

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Introduction

The Technical Conditions (Announcement, 2022) introduces new requirements for thermal insulation from December 31, 2020 by tightening the requirements regarding the limit values of the heat transfer coefficient $U_{c(max)}$ [W/(m^2·K)] for external partitions and the value limits of the demand for non-renewable primary energy EP [kWh/(m^2·year)] for the entire building. However, the Technical Conditions (Announcement, 2022) does not formulate requirements for limiting heat

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losses through joints of external partitions, also known as thermal bridges. However, it should be significantly emphasized that these are the so-called "weak spots" where there is:

- increased heat flow through the joint, which increases the value of heat loss coefficients through penetration H_{Tr} [W/K] and consequently the utility energy demand indicator EU [kWh/(m^2·year)],
- lowering of the temperature on the inner surface of the partition, which leads to the risk of surface condensation (risk of mold and fungi development), which can be determined by determining the temperature factor $f_{Rsi(2D)}$, $f_{Rsi(3D)}$.

Therefore, it becomes extremely important in the design process to correctly perform detailed calculations and numerical analyses, which should be the basis for selecting construction and material solutions for external partitions and their joints (2D, 3D) (Aghasizadeh et al., 2022; Alkadri et al., 2023; Bliuc et al., 2017).

The issues of thermal physics of buildings are primarily limited to the thermal analysis of external building envelopes subjected to the influence of external and internal temperatures that change over time (Lu et al., 2020; Nagy et al., 2022). In many cases, solving heat flow comes down to determining the heat transfer through a flat building partition in a one-dimensional (1D) field, without taking into account the heat flow in two-dimensional (2D) and three-dimensional (3D) fields. However, the real (actual) field of heat exchange is usually the external partition as a part of the building, i.e. connected by a system of joints to the connecting partitions (ceiling, external or internal wall or floor on the ground, places disturbing its continuous character, e.g. material inserts, window and door panels, variable thermal insulation thickness). In all these cases, a temperature field appears: flat (2D) or spatial (3D), which significantly changes the procedure for conducting thermal and humidity calculations of the partition (Quinten & Feldheim, 2019; Šadauskienė et al., 2022). If the resulting flat or spatial temperature field significantly changes the straight course of isotherms and adiabats formed in a one-dimensional field by bending them, then we can talk about a thermal (thermal) bridge in the partition or joint (Dylla, 2009; Dylla, 2015; Dylla & Pawłowski, 2015).

Moreover, the research on thermal bridges is a very important issue when investigating the energy efficiency of buildings (Bui et al., 2020; Ge et al., 2021; Krause, 2017; O'Grady et al., 2017). In calculations, thermal bridges are very often included as an additional element to the calculated heat transfer coefficient (Saied et al., 2021; Theodosiou et al., 2021; Zhang et al., 2022). In studies on thermal bridges and their influence on heat losses in a building, a two-dimensional FEM model in a steady state is often used to model structural nodes (Borelli et al., 2020; Kim & Yeo, 2020). The assessment process of the energy efficiency of well-insulated buildings often neglect thermal bridges, even though they can play a role in heat loss through a building envelope (Smusz et al. 2023; Tudiwer et al., 2019; Xue et al., 2023).

It should be emphasized that the currently calculated values of the heat transfer coefficient U_c and the limit values $U_{c(max)}$, $U_{(max)}$ according to the Technical Conditions (Announcement, 2022) for a single partition, do not take into account additional heat losses resulting from the occurrence of thermal bridges (2D and 3D). Their share is taken into account when determining the heat loss coefficient through penetration H_{Tr}. As part of this work, the connection between the external wall and the window was selected for calculations and analyses.

1. Physical design of the connection between the external wall and the window

The connection of the external wall with the window (in cross-section through the door frame, window sill, lintel) is a connection of two external partitions with different heat transfer coefficients U and occurs in every building. Correct design of the external wall and transparent partition, according to the thermal criterion, involves meeting the basic criterion $U \leq U_{max}$ (Adamus & Pomada, 2023; Choi et al., 2022).

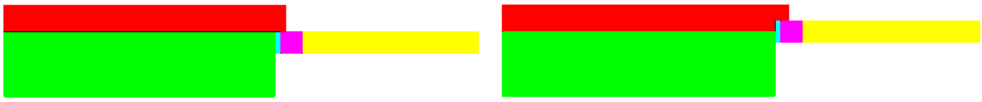
A comprehensive assessment of the thermal quality of elements of modern buildings (e.g. low-energy buildings) includes the analysis of many physical parameters. For this purpose, detailed calculations are performed using an appropriate computer program. The obtained values depend on the construction products used (including construction and insulation), including the type and thickness of thermal insulation and the shape of the material structure of the analyzed joint. The use of approximate and indicative values, e.g. in accordance with PN-EN ISO 14683:2017 becomes unjustified because they do not take into account changes in material systems and the type and thickness of thermal insulation (Pawłowski, 2020).

Table 1 lists the values of the linear heat transfer coefficient for selected variants of the connection between an external wall and a window presented in PN-EN ISO 14683:2017.

Table 1. Values of the linear heat transfer coefficient Ψ [W/(m·K) for the connection of an external wall with a window presented in PN-EN ISO 14683:2017

Thermal bridge symbol	Ψ [W/(m·K)
W1 (double-layer wall, window frame from the outside)	0.00
W4 (single-layer wall, window frame from the outside)	0.15
W5 (three-layer wall, window frame from the outside)	0.40
W7 (double-layer wall, window frame inside)	0.45
W10 (single-layer wall, window frame inside)	0.10
W11 (three-layer wall, window frame inside)	0.00
W13 (double-layer wall, window frame from the inside)	0.80
W16 (single-layer wall, window frame from the inside)	0.15
W17 (three-layer wall, window frame from the inside)	0.40

It should also be emphasized that the drawings presented in PN-EN ISO 14683:2017 are schematic and do not correspond to contemporary trends in the design of this type of joints (embedding the window in the structural layer with a jamb or embedding the window on the border of the structural and insulating layer (the so-called “warm installation” – Figure 1).

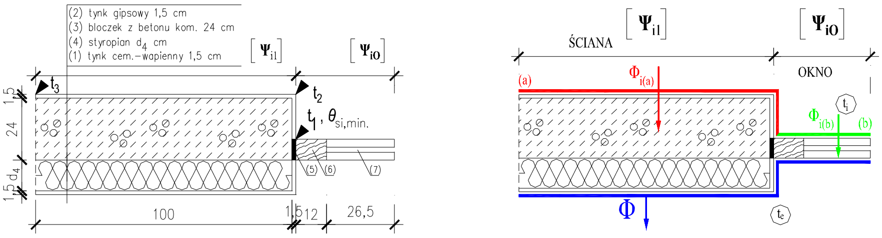


a) connection of the external wall with a window with a jamb

b) connection of the external wall with the window – warm installation

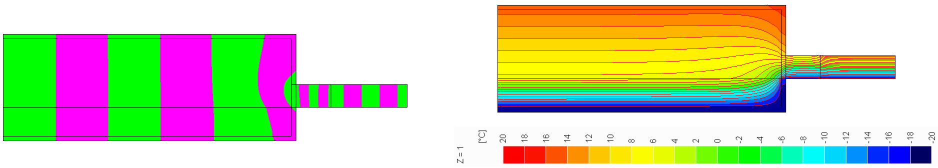
Fig. 1. Examples of solutions for connecting an external wall with a window (*own research*)

When calculating heat losses through part of the building envelope, branch (partial) values of the heat transfer coefficient Ψ should be used. Thermal bridge studies and catalogues lack the value of such a parameter, which makes it impossible to perform the correct calculations in the field of building physics, e.g. the heat transfer coefficient taking into account thermal bridges U_k. Typically, Ψ values are given for the entire additional heat loss through the bridge. However, the PN-EN 12831:2006 standard notes the need to divide them when calculating heat losses “by the room-by-room method” and proposes that: “... the total Ψ_i values calculated according to EN ISO 10211-1 should be divided into two ...”. In many cases, such behavior is a basic mistake. In order to correctly perform thermal calculations related to certain parts of the building, e.g. individual external walls or transparent partitions, the Ψ coefficient values should be divided into appropriate branches of the joint contributing to heat losses. Figure 2 shows, for selected joints, an exemplary division of joints and a graphical presentation of the calculated results.



a) computational model

b) division of the joint into parts



c) heat flux lines – adiabats

d) temperature distribution – isotherms

Fig. 2. Procedure for calculating the physical parameters of the connection between an external wall and a window in the cross-section through the frame (*own research*)

The procedure for calculating the branch heat transfer coefficients Ψ involves:

- separation of internal branches of the thermal bridge, assignment of initial and boundary conditions,
- calculation (numerically) using a computer program of heat fluxes flowing through the separated branches (parts) of the bridge,
- calculation of appropriate branch coefficients according to appropriate relationships using data corresponding to the separated branches.

The risk of mold growth at the location of the thermal bridge is checked by comparing the design value of the temperature factor $f_{Rsi(2D)}$ at the location of the thermal bridge with the limit (critical) value $f_{Rsi(crit.)}$. If the inequality $f_{Rsi(2D)} \geq f_{Rsi(crit.)}$ is met, there is no risk of mold growth on the internal surface of the partition. The critical temperature factor $f_{Rsi(crit.)}$ can be determined: in a simplified way in the case of $t_i = 20°C$, $\varphi = 50\%$, $f_{Rsi(crit.)} = 0.72$ or precisely. The limit (critical) value of the temperature factor $f_{Rsi(crit.)}$ depends on the internal air parameters (temperature t_i, humidity – room humidity class determined according to the PN-EN ISO 13788:2003 standard) and external air parameters (temperature t_e, relative humidity φ_e). Calculation procedures in this regard are presented, among others: in the author's works. The limit (critical) value of the temperature factor $f_{Rsi(crit.)}$ in the case of the third class of humidity in the room at $t_i = 20°C$ is respectively: $f_{Rsi(crit.)} = 0.785$ in the case of Bydgoszcz, and in the case of Warsaw $f_{Rsi(crit.)} = 0.789$ (Pawłowski, 2021).

2. Determining the physical parameters of the external wall connection with window

The connection between an external wall and a window in the cross-section through the lintel was selected for calculations, with different material arrangements and the location of the window in the external wall. Achieving a relatively low value for the heat transfer coefficient of the outer wall (U_c) and the transparent partition (U_w) does not guarantee the effect of minimizing heat losses through H_{Tr} transfer and limiting the occurrence of surface condensation (lowering the temperature on the inner surface of the partition) and interlayer condensation.

The following assumptions were made for calculations in the TRISCO-KOBRU 86 computer program:

- model joints were made in accordance with the principles presented in PN-EN ISO 10211:2008;
- heat transfer resistances (R_{si}, R_{se}) were assumed in accordance with PN-EN ISO 6946:2017 when calculating heat flows ($R_{si} = 0.13$ (m^2·K)/W – in the case of horizontal heat flow; $R_{se} = 0.04$ (m^2·K)/W)) and according to PN-EN ISO 13788:2017 when calculating the temperature distribution and the temperature factor f_{Rsi} ($R_{si} = 0.13$ (m^2·K)/W for frames and glazing, $R_{si} = 0.25$ (m^2·K)/W in other cases; $R_{se} = 0.04$ (m^2·K)/W);
- indoor air temperature $t_i = 20°C$ (living room); outdoor air temperature $t_e = -20°C$ (zone III);

- material solutions for joints: gypsum plaster 1 cm with $\lambda = 0.40$ W/(m·K), aerated concrete block, thickness 24 cm with $\lambda = 0.21$ W/(m·K), graphite styrofoam, thickness 15 cm with $\lambda = 0.031$ W/(m·K), thin-layer plaster 0.5 cm with $\lambda = 0.76$ W/(m·K), polyurethane foam boards, thickness 15 cm / 20 cm with $\lambda = 0.024$ W/(m·K), window frame with $U_f = 0.855$ W/(m^2·K), glazing unit with $U_g = 0.855$ W/(m^2·K);
- calculation variants: I (without a jamb), II (with a jamb), III (so-called warm installation) – Figure 3-5.

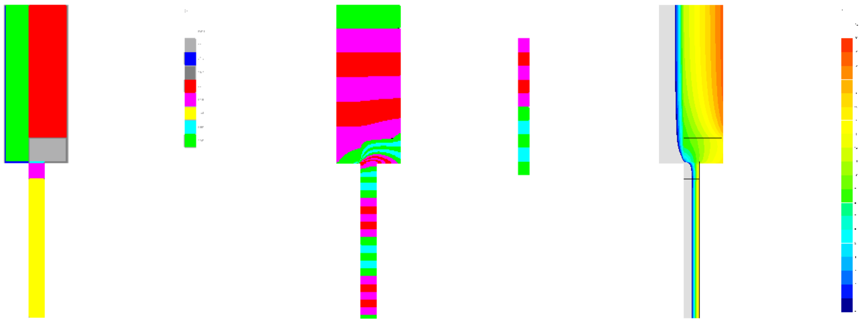


Fig. 3. Calculation model, heat flux lines (adiabates) and temperature distribution in the junction – variant I (*own research*)

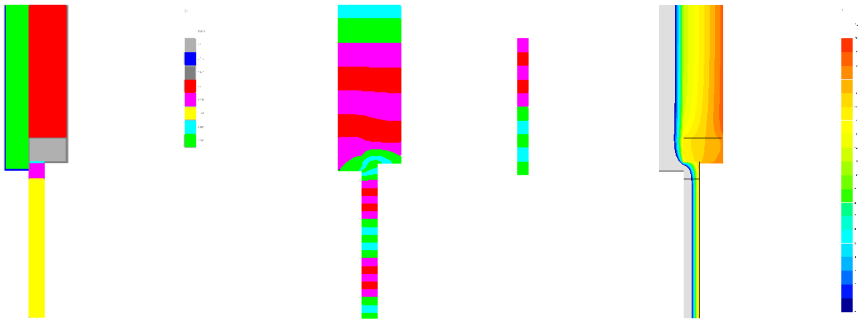


Fig. 4. Calculation model, heat flux lines (adiabates) and temperature distribution in the junction – variant II (*own research*)

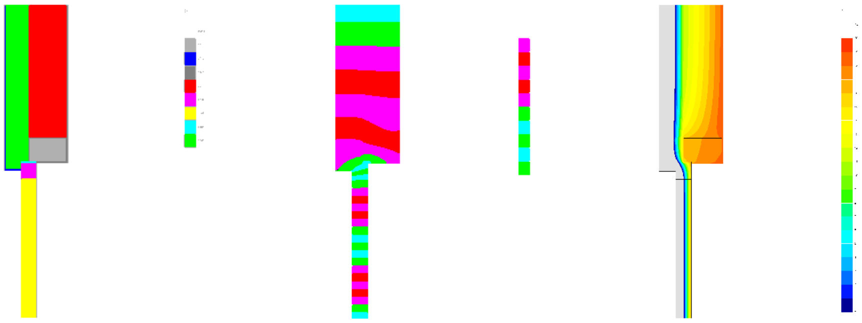


Fig. 5. Calculation model, heat flux lines (adiabates) and temperature distribution in the junction – variant III (*own research*)

The results of calculations of physical parameters depending on the material arrangement of the external wall and the location of the window are summarized in Table 2.

Table 2. Results of calculations of the physical parameters of the analyzed joints (*own research*)

Computational variant U_c [W/(m·K)]		Heat flux [W]			Linear heat transfer coefficient [W/(m·K)]			Mold risk assessment	
		Φ	$\Phi_{śc.}$	$\Phi_{o.}$	Ψ_i	$\Psi_{i,śc.}$	$\Psi_{i,o.}$	$t_{min.}$ [°C]	$f_{Rsi(2D)}$ [–]
I (a)	0.162	36.40	15.53	20.87	0.209	0.221	–0.012	11.78	0.795
I (b)	0.132	35.16	14.32	20.84	0.210	0.223	–0.013	12.05	0.801
I (c)	0.103	34.20	13.37	20.83	0.211	0.224	–0.013	12.19	0.805
II (a)	0.162	29.31	9.10	20.21	0.067	0.061	0.006	16.27	0.907
II (b)	0.132	27.87	7.70	20.17	0.064	0.058	0.006	16.36	0.909
II (c)	0.103	26.77	6.63	20.15	0.063	0.056	0.007	16.37	0.909
III (a)	0.162	28,46	8.11	20.35	0.042	0.036	0.006	16.20	0.905
III (b)	0.132	27.09	6.77	20.32	0.042	0.034	0.008	16.21	0.905
III (c)	0.103	25.96	5.67	20.30	0.041	0.032	0.009	16.23	0.906

(a) – insulation made of graphite polystyrene. 15 cm; (b) – insulation made of polyurethane foam, thickness 15 cm; (c) – insulation made of polyurethane foam, thickness 20 cm; U_c – heat transfer coefficient of the external wall; Φ – heat flux flowing through the entire joint; $\Phi_{śc.}$ – heat flux flowing through the wall; $\Phi_{o.}$ – heat flux flowing through the window; Ψ_i – linear heat transfer coefficient for the entire joint; $\Psi_{i,sc.}$ – linear heat transfer coefficient through the external wall; $\Psi_{i,o.}$ – linear heat transfer coefficient through the window; $t_{min.}$ – minimum temperature on the inner surface of the partition at the thermal bridge; $f_{Rsi(2D)}$ – temperature factor

A large (significant) value of the Ψ coefficient does not automatically mean a significant thermal bridge. According to the definition, Ψ values are treated as correction factors for the calculation of one-dimensional heat losses, by means of which the geometric aspect (determined by the adoption of dimensions) should be taken into account, as well as the increase in heat flux. An example of the classification of the impact of thermal bridges depending on the value of the linear heat transfer coefficient Ψ is given in Table 3.

Table 3. Classification of the impact of thermal bridges on heat losses (Wouters et al., 2002)

Thermal bridge impact classes based on the assessment of the Ψ coefficient value			
C1 $\Psi_{i,e} < 0.1$	C2 $0.1 \leq \Psi_{i,e} < 0.25$	C3 $0.25 \leq \Psi_{i,e} < 0.5$	C4 $\Psi_{i,e} \geq 0.50$
influence negligible	little impact	huge impact	very big influence

The physical parameters of the connection between the external wall and the window in the cross-section through the lintel depend on the arrangement of the material layers of the joint: e.g. type and thickness of thermal insulation, window location.

Improper shape of the arrangement of material layers (lack of a recess) causes increased heat losses in the form of heat flux Φ [W] and the linear heat transfer coefficient Ψ [W/(m·K)] and a decrease in the temperature on the internal surface of the partition in place of the thermal bridge $t_{min.}$ [°C], which may lead to the risk of condensation on the inner surface of the partition (Table 2).

Based on the calculation results (Table 2), it was found that in the case of incorrect (faulty) shape of the material layers of the joint (variant I), the impact of the thermal bridge is much higher than in variants II and III. However, the use of a solution with a jamb or the so-called warm installation (variants II, III) reduces heat losses resulting from the occurrence of a linear thermal bridge to the value of $\Psi_i = 0.041\text{-}0.061$ W/(m·K) and the effect of the bridge is omitted (Table 3). The values of the linear heat transfer coefficient Ψ are used to calculate heat losses through H_{Tr} determining the energy balance of the building. It should also be emphasized that there is no risk of surface condensation in the analyzed joints.

Analyzes regarding shaping the connection between the external wall and the window were presented, among others, in the works (Jezierski & Borowska, 2018; Pawłowski, 2020; Pawłowski, 2021).

Conclusion

Taking into account the thermal criterion (minimization of heat losses through building partitions taking into account the stationary heat flow in the 2D and 3D field) and the humidity criterion (limiting the occurrence of surface condensation), it is possible to correctly shape the systems of material layers of the cladding of newly designed and modernized buildings.

Determining the thermal-humidity characteristics of building envelope elements taking into account innovative insulating materials, the correct location of the window in the wall and using a computer program allows for the obtaining of reliable results reflecting actual heat losses. Taking into account the variable parameters of internal and external air is important in shaping the systems of material layers of external partitions and joints in terms of heat and humidity.

It becomes justified to specify the maximum value of the linear heat transfer coefficient $\Psi_{max.}$ in the Technical Conditions (Announcement, 2022) two-dimensional (2D) connectors. It is also proposed to withdraw the limit value of the temperature factor f_{Rsi} at the level of 0.72 from the Technical Conditions (Announcement, 2022) and to determine the limit (critical) f_{Rsi} values for the selected location of the building and the conditions of its use. This will eliminate incorrectly designed structural nodes.

There is a need to conduct further calculations in this area and to develop a catalogue of thermal bridges for modern buildings.

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