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Short communication

Numerical investigation of buildings point thermal bridges observed on window-thermal insulation interface

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A R T I C L E I N F O

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A B S T R A C T

Practices to avoid thermal bridges in the building shell, consists one of the key elements in the comprehensive assessment of the energy behaviour of buildings. As we are moving fast to the era of nearly zero energy buildings, both the use of non-invasive measurement techniques as well as the use of analytical and numerical models, have intensified research and substantiated best practices around this interesting issue. The sole criterion of the energy assessment of thermal bridges is the reduction of the heat losses, thus heat transfer analysis dominates the field.

This short technical note presents and analyses the thermal behaviour of point thermal bridges, observed in areas of higher thermal transmittance at the joints of windows and supporting structures through different types of fasteners. Specifically, the method of direct support of windows in a layer of stone wool is considered, and the energy performance of three alternative ways of supporting the construction is examined. The heat transfer assessment of the investigated solutions is conducted with the use of numerical analysis, performed with the use of two analytical tools (THERM and HEAT3), in two- and three dimensional domains. The work concludes with substantiated suggestions in relation to the solutions that are proposed, always guided by the reduction in energy consumption. The paper aspires to provide informed answers to engineers and researchers in the field of energy efficiency of buildings, thus creating the field for future developments in the field of point thermal point bridges in window.

1. Introduction

Windows are considered to be the weakest link of the energy behaviour of buildings. Heat losses from windows concern both those fluxing from the fenestration, due to its inferior thermophysical properties in relation to the masonry, but also losses due to thermal bridges observed at the joint between the structure and the window [2]. Smart practices of window installation consist one of the main

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Nomenclature

Symbol

A	Area over which the value U or Ψ applies m^2
a	Start point for average point thermal transmittance calculation -
b	End point for average point thermal transmittance calculation -
l	length over which the value of U or Ψ applies m
H	Heat loss W
L_{2D}	Linear thermal coupling coefficient ([1] W/mK)
L_{3D}	3D thermal coupling coefficient ([1] W/mK)
N	Number of components -
n	Average number of fasteners per meter -
U	Thermal transmittance of a one-dimensional component (W/m^2K)

Indicator

1	Case study 1 (one corner element, one middle element, on W48 element)
2	Case study 2 (two corner elements, two W48 elements)
C	Complex construction
CL	Corner Element
EL	Middle Element
i	One dimensional
j	Two dimensional
S	Sum of individual components
ST	Standard Structure
SWB	Stone wool board
T	Total
W48	W48 Element
α,β,γ	Different types of parts

Greek symbol

Δ	Change in a value -
λ	Thermal Conductivity (W/mK)
χ	Point thermal transmittance (W/K)
ψ	Linear thermal transmittance (W/mK)

Abbreviation

CEN	European Committee for Standardization
EU	European Union
nZEB	Nearly Zero Energy Buildings

challenges the community of building physicists and the construction practitioners are facing, towards achieving buildings of higher efficiency [3]. National regulations are becoming stricter in defining the minimum requirements that the thermal performance of thermal bridges should fulfil [4]. As a representative example of the minimum requirements of a European Union (EU) member state, the case of Lithuania is referred, where the thermal transmittance of a linear thermal bridge of a nearly zero energy buildings (NZEB) should not exceed 0.05 W/(mK) [5]. It is evident that in order to meet these energy behaviour demands, particular effort is required, both at the level of industrial development as well as in the field of research analysis [6].

Currently, different structural solutions are applied for the installation of window frames in masonries. In most cases, window frames are hung on reinforced plastic fasteners or steel anchor fasteners that are protruding on the building wall (see Fig. 1a). Windows are also often installed on rectangular frames that are protruding on the isolated side of the wall. Such frames are made of metal profiles, wooden beams and reinforced plastic elements [7]. For individual house construction, frames made out of chipboard, similar to boxes in appearance may also be used (see Fig. 1b). Unfortunately, these different variations of window frames' installation elements often become thermal bridges that are difficult to define. Also by using the aforementioned window installation methods, the risk of surface condensation and mould growth increases [8]. Based on the fact that the Passive House Institute states that the required maximum of passive house partitions airtightness must be 0.6 air changes per hour at 50 Pa pressure [9], it is severely difficult to eliminate these defects in passive houses, hence, risking their certified status as low energy buildings. [10].

A recent, new practice applied concerns the installation of window frames directly onto thermal insulation layers (see Fig. 1c). In this case, point thermal bridges are observed at the joints of the window frame and the fasteners used to fix the window on the building shell. The number of these point thermal bridges depends on the length between the structure of the wall and the window, and on the materials used to install the window, such as mounting foam, frame, fasteners and finishing plaster. In order to reduce the energy losses due to point thermal bridges, anchor fasteners made of plastic or fiberglass are often used. The thermal conductivity of such materials is

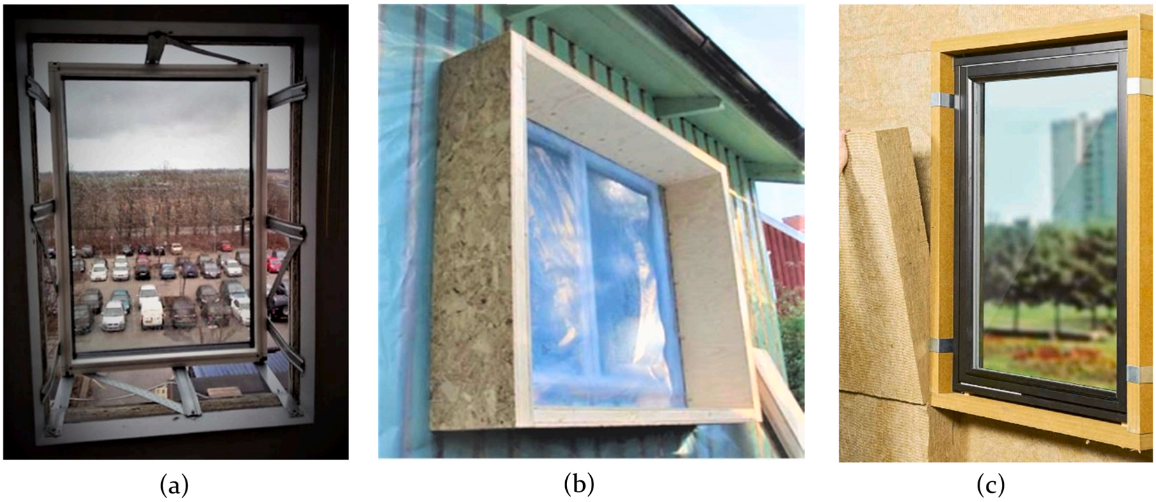

Fig. 1. Installation of window frames practices; (a) on anchor fasteners (left); (b) on chipboard frame(middle); (c) in stone wool boards (right).

much less than that of stainless steel. However, the structural properties of plastic and fiberglass fasteners are inferior, compared to metallic fasteners, resulting in limitations in their application, especially concerning heavy type windows [11].

The installation of window frames directly onto thermal insulation layers consists a promising technique, which though is still not sufficiently investigated, with regard to its thermal performance. This study intends to investigate the thermal behavior of point thermal bridges which result from the installation of openings on layers of stone wool, using different fasteners. For the purpose of the implementation of this study, different types of fasteners as well as different installation and operating conditions are considered and investigated. With the use of numerical tools. This work seeks to provide informed answers to the scientific and the engineering community, regarding the thermal performance of this particular method compared to other conventional methods.

2. Methods and materials

2.1. Physics of point thermal bridges heat transfer analysis

In terms of this study, the physics for the calculatoin of the heat transfer from point thermal bridges, followed the requirements of the ISO 10211:2017 standard ([1].

Particularly the linear thermal transmittance with calculated with the use of Eq. (1).

$$\psi = L_{2D} - \sum U_j l_j \tag{1}$$

The point thermal transmittance is calculated as in Eq. (2):

$$\chi = L_{3D} - \sum_{i=1}^{N_i} U_i A_i - \sum_{j=1}^{N_j} \Psi_j \tag{2}$$

The average point thermal transmittance $\overline{\chi}$, was calculating using Eq. (3):

$$\overline{\chi} = \frac{\int_a^b \chi \quad dl}{b-a} \tag{3}$$

The longitudinal thermal transmittance $\Delta\psi_S$ was defined as the sum of the point thermal transmittance of the individual components, calculated according to Eq. (4).

$$\Delta\psi_S = \quad (n\chi)_a + (n\chi)_\beta + \ldots + (n\chi)_\gamma \tag{4}$$

The total linear thermal transmittance was also calculated analytically with the use of HEAT3 application, referred in this study as the calculation procedure of the complex structure, denoted with indicator C.

The total linear thermal transmittance of the thermal bridges was calculated based on the sum-up of the linear thermal transmittance of the individual components, and the thermal transmittance of the stone wool construction, in accordance to Eq. (5).

$$\psi_{TS} = \psi_{SWB} + \Delta\psi_S \tag{5}$$

or by considering the linear thermal transmittance of the complex structure, in accordance to Eq. (6).

$$\psi_{TC} = \psi_{SWB} + \Delta\psi_C \tag{6}$$

The analytical solutions of the above set of equations for the investigated case studies were obtained with the use of the THERM [12] and the HEAT3 [13] software. Particularly THERM was used for the two dimensional solutions whereas HEAT3 was applied for 3D problems.

The caluclations were conducted in two steps:

- By considering the installation of the window structure in a masonry layer, without the existence of an insulation element, using THERM
- With the use of insulation materials and thermal fasteners, with the use of HEAT3.

An analysis was also conducted to reveal the impact of the location of the window in the insulation layer on the heat losses. The calculations were made by varying the distance from the edge of the masonry to the installation location of the window frame. In terms of this study, two cases of window frame installations in stone wool boards were considered:

- A 1 m high wall fragment with three fasteners installed: corner piece CL, middle piece EL and window fastener W48; (Case Study 1 – indicator 1)
- A 1 m long window opening with two corner elements CL and two window fasteners W48 (Case Study 2 – indicator 2)

The calculation procedure employed in this study, is summarized in Fig. 2.

2.2. Analysed construction

In terms of this study, the heat losses due to point thermal bridges at the windows and thermal insulation interface, with the use of different types of fasteners were determined. The thermophysical properties of the masonry assumed for the purposes of this work, as well as the overall thermal transmittance (U Value) are provided in Table 1.

As far as the window is concerned, a three-pane fenestration (48 mm double-glazed unit, two of which with a selective coating), with plastic thermal frames, placed at a distance of 20 mm was assumed. The window frame was of 6 chambers and its thickness was 100 mm with a heat transfer coefficient value of $U_f = 1.06 W/m^2K$. The window was considered to be installed on the opening edge of the building using stone wool boards (See Fig. 3a); a rigid mineral wool board ($k = 0.035 W/m^2K$) was assumed for the window installation (Fig. 3b).

Table 2 provides the dimensions of the fasteners considered in this study. The fasteners are depicted in Fig. 4 Two wall mounting parts measuring 80 × 100 mm were evaluated in the calculations.

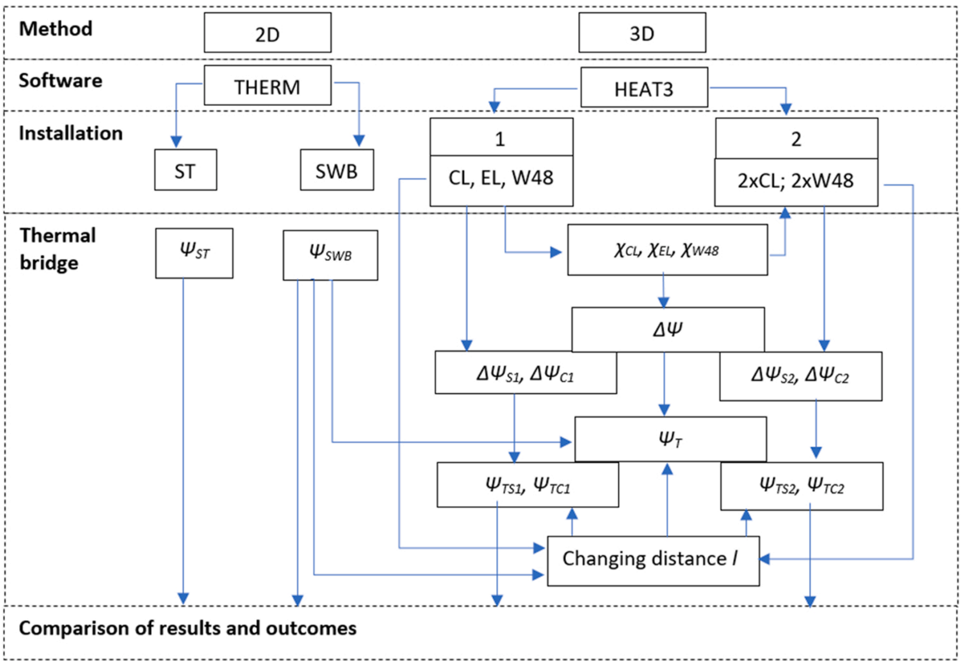

Fig. 2. Calculation process of this study.

Table 1
Thermophysical properties and U Value (in accordance to [14]) of the construction analysed.

Building Material	Thickness [m]	Thermal Conductivity [W/mK]	Thermal Resistance [m^2K/W]
Plaster	0,1	1	1
Masonry	0,25	0,5	0,5
Thermal Insulation	0,25	0035	7,1
Plaster	0,1	1	1
Internal Thermal Resistance Ri			0,13
External Thermal Resistance Re			0,04
U Value [W/m^2K]			**0,12**

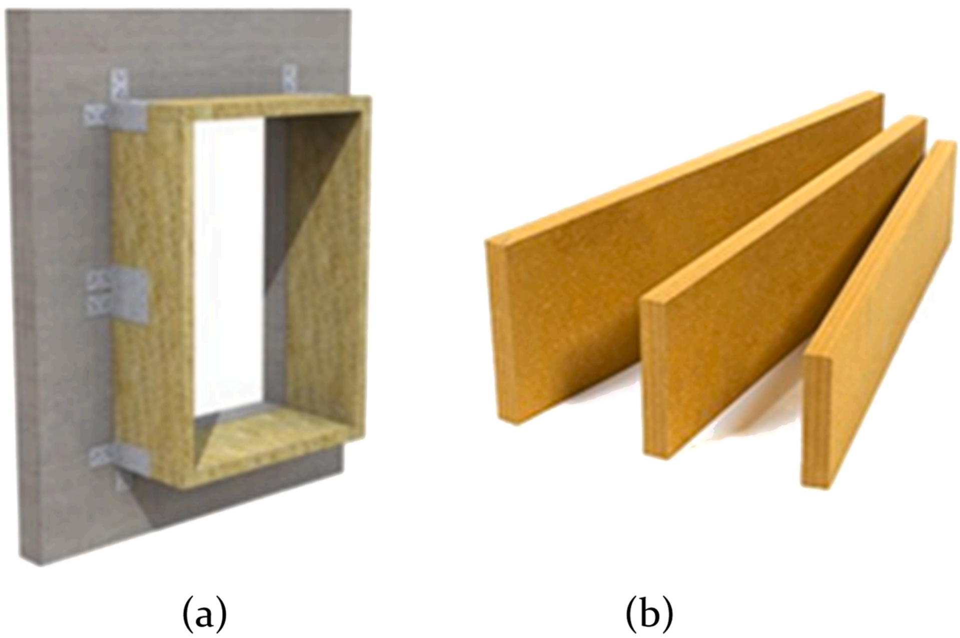

Fig. 3. Window opening construction considered in this study. (a) Window opening construction (left) and (b) rigid stone wool boards (right).

Table 2
Fasteners dimensions.

	Length [mm]	Width [mm]	Thickness [mm]
W48 profile	192	50	2
Corner Element (CL)	192	192	2
Middle Element (EL)	80	100	2

3. Results

3.1. Linear thermal transmittance without assessing window fasteners

In Fig. 5, the calculation of the linear thermal transmittance ψ_T, for the case of the installation of the window on the masonry layer is shown. According to this figure, the average value of the linear thermal transmittance, calculated with THERM, is 0.13 W/mK.

Fig. 6, presents the linear transmittance ψ [W/mK], versus the linear installation distance from the supporting wall, for the case of the use of installing the window over a thermal insulation layer. As it can be obtained from this figure, the lowest linear thermal bridge value ψ_{SWB} is 0.026 [W/(mK)] and is observed when the window installation site is at the centre of the thermal insulation material; namely at a distance of 60–100 mm from the supporting masonry layer. It is also worth noting that the graph is symmetrical around the minimum. This is due to the fact that at the boundaries, the window opening acts either as a cold sink or as a hot source (at 0 mm and 150 mm respectively), as there is only insulating material on one side of the window.

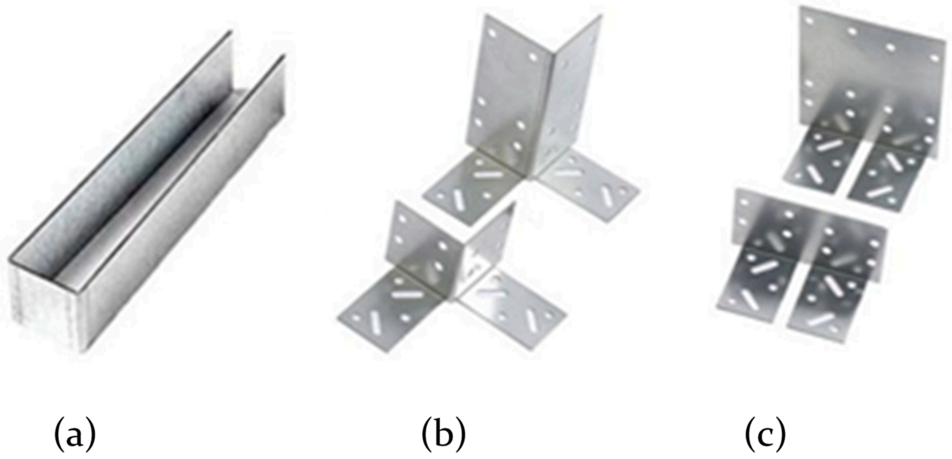

Fig. 4. Installation of window frames practices; (a) W48 profile (left); (b) corner Fitting (CL)(middle); (c) middle part (EL) (right).

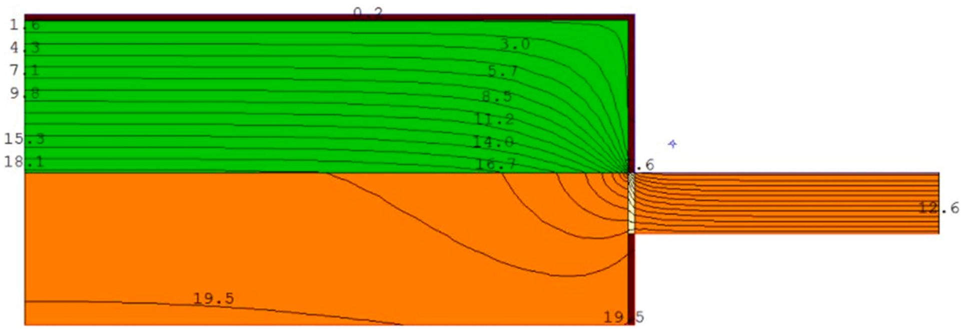

Fig. 5. Linear thermal transmittance ψ isolines [W/mK] for window installation on the masonry layer.

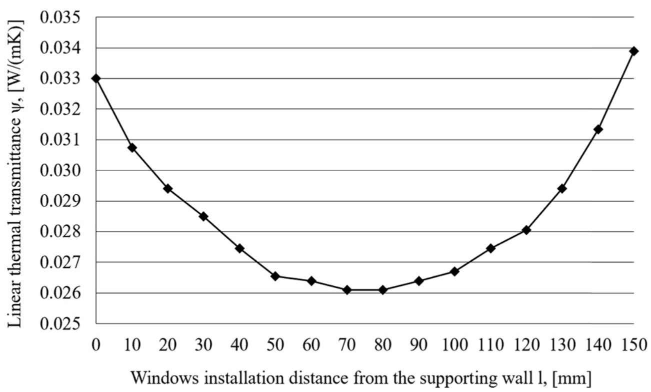

Fig. 6. Linear thermal transmittance ψ [W/mK] versus linear installation distance from supporting wall l [mm].

3.2. *Linear thermal transmittance by assessing window fasteners*

In Fig. 7, the influence of fasteners on heat losses is depicted. The results reveal that the thermal transmittance of the corner and the midpoint element at $l = 50mm$ is higher and it is reduced as the distance from the supporting wall increases. As far as the W48 element is concerned, the thermal performance of the point thermal transmittance increases with increased window installation distance, and has its highest value at $l = 150mm$.

A comparison of the linear thermal transmittance ψ for different boundary conditions, as analyzed in this study, is presented in Fig. 8. The results of this study reveal that the linear thermal transmittance ψ of the standard installation site, delivers the highest

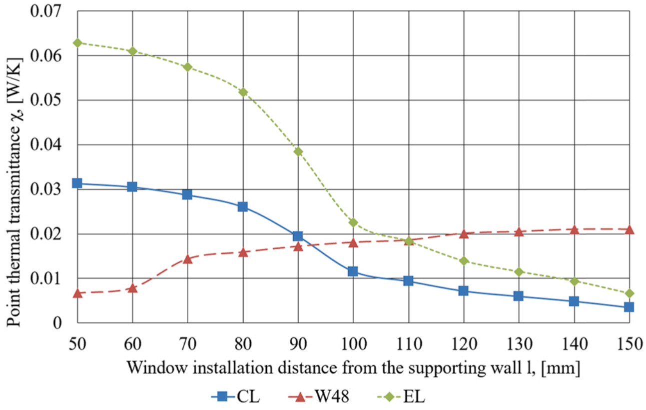

Fig. 7. Point thermal transmittance χ [W/K] of individual fasteners versus linear installation distance from supporting wall l [mm].

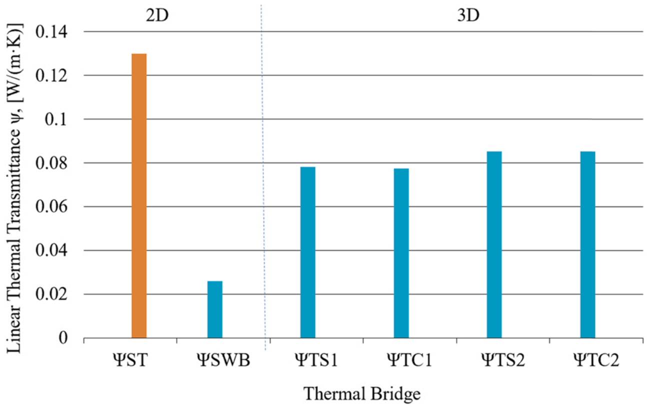

Fig. 8. Linear thermal transmittance ψ [W/K] of different thermal bridges [mm].

values, while using stone wool boards for window frame insulation, reduce the value of ψ by one order of magnitude. If, however, the impact of the metal fasteners on the heat losses is also considered, the reduction of the linear thermal transmittance is limited to an average difference of 37%.

The assessment of the thermal heat losses for different locations of the fasteners, reveals that when the window is installed right next to the edge of the masonry (l = 0 mm), the linear thermal transmittance Ψ remains almost equal to the complex thermal bridge. Therefore, the results of the calculation according to the methodology specified in [1] differ insignificantly from the calculated values provided with the application of HEAT3 model. However, if the change in the installation location of the window frame in relation to the thermal insulation layer is assessed, a discrepancy between the results of the different methodologies is observed.

The impact of the values of the total linear thermal transmittance ψ_T on the window installation location was examined, using alternative calculation methods, and particularly the summed calculation option $\Delta\psi_S$ and the complex method $\Delta\psi_C$. The results (Fig. 9), which concern the case study 2, show that the values obtained by estimating the sum of the point thermal bridge values $\Delta\Psi_{S2}$ of individual metal fasteners may differ from 26% to 41% compared to the complex values $\Delta\Psi_{C2}$. As the installation distance of the window frame from the load-bearing wall increases, the difference between the values of the linear thermal transmittance, obtained by different methods, also increases.

The results also reveal that in cases where the sum of the total linear thermal transmittance $\Delta\psi_{S2}$ is considered, for a window installed at a distance of 50–100 mm from the masonry layer, the value of the linear thermal transmittance increases by 28% compared to the values of transmittance at a distance of 100–150 mm from the load-bearing wall. The highest value of the linear thermal transmittance, is observed at a distance of 70 mm, and the lowest value of ψ_{T2} is calculated at 130 mm from the masonry layer. As a general conclusion, it can be stated that by applying $\Delta\psi_{C2}$ and installing the window in the thermal insulation layer at a distance of 50–100 mm from the masonry layer, increased values of linear thermal transmittance by 30% are observed, compared to the values of linear thermal transmittance at a distance of 100–150 mm from the retaining wall.

4. Discussion

The main objective of this study was to investigate the impact of fasteners used in window-construction interfaces on thermal

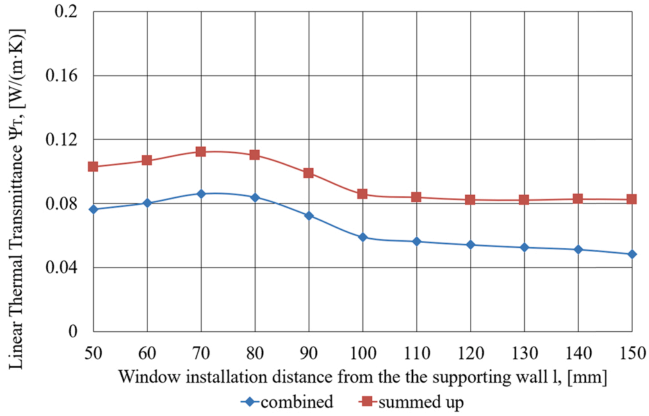

Fig. 9. Total linear thermal transmittance ψ_T [W/mK] versus linear installation distance from supporting wall l [mm] for complex (C) and summed-up (S) method for case study 2.

bridges, in cases the window opening structure is directly fixed on a thermal insulating material, specifically on stone wool. The findings of this study revealed that the wide spread notion of the building physicist's community for negligible thermal losses due to point thermal bridges, when installing the window structure directly on a thermal insulation layer is incorrect. It was though shown that with this construction solution, the losses from the linear thermal bridge created at the junction of the wall and the window frame can be reduced up to 37%. This finding agrees with results discussed in other studies, where the linear thermal transmittance was not reduced more than 50% [15].

In this study, the effect on thermal losses of each individual fastener element (corner, middle and W48 element) was examined. The calculations revealed that the point thermal transmittance of the middle element is the higher, followed by the W48 and the corner element losses (Table 3). This result is an indication that the design and installation of windows on thermal insulation layers should avoid the use of middle elements, as much as possible, given that all structural requirements are fulfilled.

As far as the numerical tools employed are concerned, it was revealed that the deviation between results provided by an analytical method, based on the EN ISO 10211:2017 standard and the HEAT3 tool, presented minor deviation of less than 1% ($\Delta\Psi_{S1} = 0.0521[W/K]$ and $\Delta\Psi_{C1} = 0.0515[W/K]$ respectively) The calculation results revealed also a very good agreement in the case of the calculation based on individual components and for the complex structure. The agreement though was not the precise with the increase of the installation distance l of the window frame from the load bearing construction. The total thermal bridge of the opening by summing point thermal bridge values of individual metal fasteners ($\Delta\Psi_{S2}$) may change the results by 26–41% compared to the same calculations using composite model ($\Delta\Psi_{C2}$). This deviation is due to the thermal interaction of the individual fasteners, even though they are separated by a sufficiently large layer of thermal insulation material. Thus, the necessity for employing 3D thermal numerical simulation to accurately estimate the influence of metal fasteners on heat loss is revealed. This conclusion is also reached when comparing the obtained values of the linear thermal transmittance using the 2D (THERM) and the 3D (HEAT3) calculation tool. Particularly, a deviation of close to 70% on the calculation of the linear thermal transmittance was found ($\Psi_{SWB} = 0.026[W/mK]$ versus $\Psi_T = 0.0815[W/mK]$). This finding underlines the significance of the use of 3D models and the consideration of the impact of point thermal bridges, a conclusion which is in agreement with previous relevant studies [16].

Another interesting finding of this study, related to the calculation methods employed is presented in Fig. 10. Particularly in this figure, the linear thermal transmittance ψ [W/mK] versus linear installation distance from supporting wall l [mm] for 2D and 3D calculation domains is presented. As it can be deduced from this figure, the linear thermal transmittance values decrease when increasing the installation distance for the case of the 3D domain, whereas for the 2D the trend is the opposite. This performance can be attributed to the fact that in the 3D domain calculations, the thermal interaction of the individual point thermal bridges is considered. Similar results were obtained by other researchers [17,4,18].

Considering the Case Study 2, which is a standardized installation arrangement for windows of length less than 1400 mm length, and assuming that the 3D calculation domain is the most precise, the following analytical solution, derived from Fig. 10, can be provided, for the calculation of the linear thermal transmittance of windows installed in thermal insulating layers, for installation distance over 100 mm from the wall.

Table 3
Point thermal transmittance χ [W/K] of different fasteners at installation distance 100 [mm] from wall.

	Point thermal transmittance χ [W/K]
W48 profile	0.0181
Corner Element (CL)	0.0114
Middle Element (EL)	0.0225

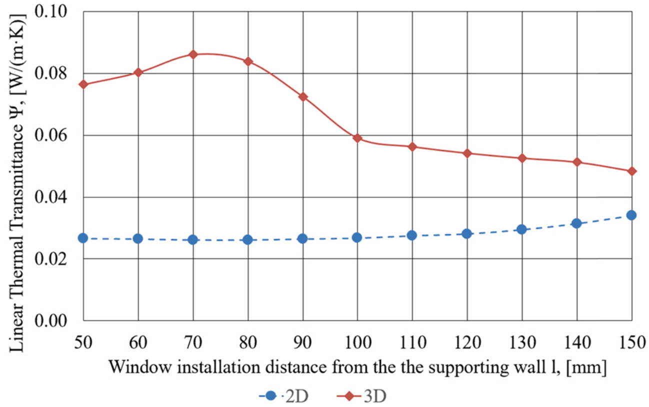

Fig. 10. Linear thermal transmittance ψ [W/mK] versus linear installation distance from supporting wall l [mm] for 2D and 3D calculation domains.

$$\psi = 2 * 10^{-4} l + 0.0787 \quad (7)$$

Fig. 11 summarizes some of the major findings of this study. This figure is tailored based on the minimum requirements of an EU member state, the legislative provisions of which are similar for many other members states of the central and northern European continent. The results reveal that should minimum legislative requirements be fulfilled, then the installation of the window structure from the supporting wall, in case directly mounted to the thermal insulating material, should not be less than 100 mm. Apparently this assessment is based on the assumptions made in this study, which are though typical for other similar structures.

5. Conclusions

In this study, a promising method of supporting window openings directly on the thermal insulation layer was investigated. Analytical, 2D and 3D numerical models were employed and compared, concluding that, in cases where losses from point thermal bridges are calculated, the numerical 3D tools give much greater accuracy in the calculations. It was also revealed that the deviation between results provided by an analytical method, based on the EN ISO 10211:2017 standard and a 3D numerical model, presented minor deviation of less than 1%In this study, an analytical solution was delivered for the calculation of the linear thermal transmittance of windows installed in thermal insulating layers, for installation distance over 100 mm from the wall. This work also proceeded to specific suggestions regarding installation guidelines of windows directly in contact with thermal insulation layers, depending on the type of fasteners that will be used, considering minimum legal requirements as well. This study seeks to support the further analysis of thermal losses of buildings, highlighting the importance of including losses from point thermal bridges, as well as to support alternative construction methods, with a view to saving energy in buildings.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

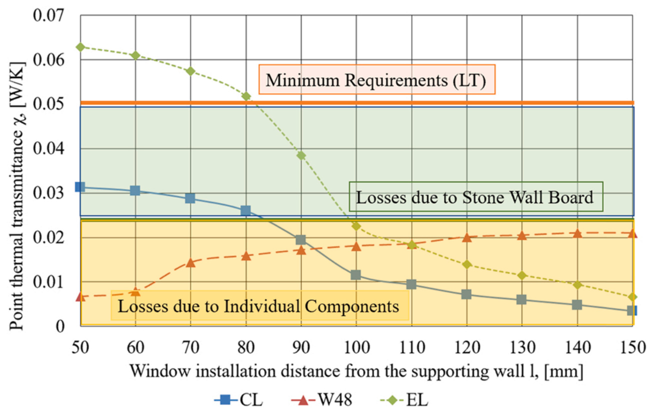

Fig. 11. Point thermal transmittance χ [W/K] of individual fasteners versus linear installation distance from supporting wall l [mm] in accordance to minimum legislative requirements.

influence the work reported in this paper.

Data accessibility

https://github.com/Jolsada/Thermal-bridges-THERM.git.
https://github.com/Jolsada/Thermal-bridges-HEAT3.git.

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