

Article

Comparative Analysis of Thermal Bridges and Condensation Risk Based on Installation Positions of Single- and Double-Window Systems in Externally and Internally Insulated Concrete Walls

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Abstract

This study investigates the thermal bridge characteristics and condensation risks associated with the installation of single- and double-window systems in externally and internally insulated concrete walls. A total of twelve configurations were evaluated by combining two window types, three installation positions (exterior, middle, and interior), and two insulation strategies. Two-dimensional and three-dimensional heat transfer simulations were conducted using ISO 10211- and ISO 10077-2-compliant methods. Both linear (Ψ) and point (χ) thermal transmittances—including those caused by mechanical brackets—were considered to derive the effective U-value ($U_{w,install}$) for each case. The results showed that placing windows on the exterior side of the insulation layer yielded the best thermal performance, while interior installations posed a higher risk of surface condensation, particularly for single windows. Although single-window systems generally exhibited superior intrinsic insulation, their thermal performance degraded more significantly than that of double windows when installation-related thermal bridges were included, especially under interior-side configurations. Additionally, the study applied the DIN 4108-2 guideline, which recommends a 30 mm insulation overlap around window frames. The application of this detail reduced thermal bridging across the evaluated configurations, with the magnitude of improvement varying depending on window type and installation position. This study provides simulation-based insights into the performance impacts of window installation details and highlights the importance of thermally optimized design strategies to minimize heat loss and condensation in high-efficiency building envelopes.

Keywords: thermal bridge; window installation; single- and double-window systems; linear thermal transmittance; point thermal transmittance; condensation risk; DIN 4108-2 guideline; effective U-value; insulated concrete wall



Academic Editor: An Cheng

Received: 14 September 2026

Revised: 15 October 2026

Accepted: 16 October 2026

Published: 19 October 2026

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1. Introduction

In recent years, global emphasis on building energy efficiency has underscored the importance of thermal performance in envelope components. Among these, windows represent one of the most thermally vulnerable parts of the building envelope due to their complex geometry and material composition. In particular, thermal bridges at window installation interfaces—including linear discontinuities and point-based fixings—have been identified as key contributors to energy loss and condensation risk.

In Germany, the Passive House Institute (PHI) [1] has set stringent criteria for passive house certification. All opaque components such as walls, roofs, and floors must exhibit thermal transmittance (U-values) of $0.15 \text{ W/m}^2\cdot\text{K}$ or less, while window systems are required to achieve glazing U-values of $0.8 \text{ W/m}^2\cdot\text{K}$ or below. Importantly, the PHI further limits the installed window U-value—including thermal bridges at the frame-to-wall interface—to a maximum of $0.85 \text{ W/m}^2\cdot\text{K}$. This requirement highlights the critical impact of installation details on overall window performance.

However, the extent to which installation-related thermal bridges are addressed in building energy regulations varies across countries. In South Korea, the Building Energy Conservation Design Standards have progressively strengthened thermal transmittance requirements for windows and opaque building components; however, they do not currently include specific provisions for thermal bridges arising at window installation interfaces. Consequently, even when individual windows and opaque building components satisfy the prescribed thermal transmittance requirements, installation-related thermal bridges can cause additional heat loss and increase the risk of surface condensation, particularly around window edges.

Window systems and installation practices likewise differ among countries and should therefore be considered when assessing installation-related thermal bridges. Several studies in South Korea have investigated the thermal effects of window installation under local window and construction conditions. Rhee et al. [2] analyzed the impact of reveal depth on heating and cooling loads in externally insulated walls, identifying notable performance differences depending on window position. However, their analysis did not account for mechanical fixings such as brackets, which are integral to real-world installation. Lee et al. [3] examined linear thermal bridges in dual-frame sliding windows, a common double-window system in South Korean buildings, but likewise excluded anchoring components. Song et al. [4] advanced the field by considering point thermal bridges caused by metal brackets, including variation in bracket shape and quantity based on window size. However, their analysis was limited to a single installation detail—between concrete and insulation—and did not compare alternative installation positions. Three-dimensional analyses further indicate that point thermal bridging is affected by the configuration and location of fastening or supporting components, while two- and three-dimensional methodologies can yield substantially different thermal bridge assessments [5,6]. This distinction motivates the combined use of two- and three-dimensional analyses in the present study.

Building on this line of work, the authors previously investigated the influence of window installation position on thermal bridging in externally insulated concrete wall assemblies [7]. However, internally insulated wall systems continue to be used in South Korean residential buildings, while previous studies on window installation thermal bridges have predominantly focused on externally insulated wall assemblies. This highlights the need to extend the assessment to internally insulated configurations and to examine whether the influence of window installation differs between the two insulation strategies. The present study therefore considers both external and internal insulation configurations, enabling a comparative assessment of how insulation strategy interacts with window type and installation position. In internally insulated walls, the concrete structure remains on the cold side of the insulation, so that any interruption of the insulation layer at the window reveal can expose cold concrete surfaces to the indoor environment. The window installation interface is therefore expected to be particularly critical for surface condensation in such walls, which makes a joint assessment of heat loss and condensation risk necessary.

International research has also recognized the thermal implications of window placement. Parametric studies across multiple wall constructions and window types have shown that the position of the window within the wall opening, particularly relative to the in-

sulation layer, is a key determinant of the linear thermal transmittance at the installation interface [8]. Cappelletti et al. [9] evaluated linear thermal bridges in clay block walls and demonstrated the influence of exterior, middle, and interior installation. Yet, their study was restricted to single-window systems and excluded mechanical fixings. Adamus and Pomada [10] investigated how wall materials such as aerated concrete or ceramic blocks influence thermal bridging around windows but did not examine differences between window types or point thermal bridges. Related work on window-to-wall installation systems further indicates that installation details that maintain insulation continuity around the frame can substantially reduce heat loss at the junction [11]. Sierra et al. [12] assessed heat loss and surface temperature variation in cavity wall openings but did not consider variations in window configuration or the effect of anchoring hardware. A recent study of highly insulated walls likewise showed that installing the window within the insulation layer and covering the frame with insulation can reduce Ψ by an order of magnitude and raise the minimum internal surface temperature, although point thermal bridges and internally insulated walls were not considered [13].

A common finding across previous studies is that installation-related thermal bridges can increase the installed window U-value relative to the nominal window U-value and can measurably affect building heating demand. Moreover, insufficiently addressed thermal bridges elevate the risk of condensation and mold growth near glazing edges. This risk is commonly evaluated by the temperature factor f_{Rsi} or, in South Korea, by the Temperature Difference Ratio (TDR), which characterize the minimum interior surface temperature independently of the overall heat loss. The reliability of this risk assessment can itself depend on how the window-to-wall junction geometry is represented in the numerical model, as simplified representations of this junction have been shown to alter predicted internal surface temperatures and heat loss at the interface [14]. However, a comprehensive framework that evaluates the combined effects of window type, installation position, and bracket-induced point thermal bridges is still lacking.

To address this gap, the present study investigates both linear and point thermal bridges in single- and double-window systems commonly used in South Korea. The analysis considers two representative insulation configurations: externally and internally insulated concrete wall assemblies. A two-dimensional heat transfer simulation (FLIXO) is employed to evaluate linear thermal transmittance and minimum surface temperature, while a three-dimensional simulation (TRISCO) is used to assess point thermal bridges caused by metal brackets. Temperature Difference Ratio (TDR) analysis is conducted to evaluate condensation risk under various installation scenarios. In addition, the study examines the performance impact of applying insulation overlap details recommended in DIN 4108-2. By integrating these factors, the study calculates effective U-values that reflect real-world installation effects, offering a realistic benchmark for evaluating window system performance.

This research aims to provide a practical foundation for developing energy-efficient and condensation-resistant window installation strategies aligned with Korean construction practices. By quantifying the influence of insulation strategy, mechanical fixings, and installation location, the study addresses a gap in existing thermal bridge research and supports the development of performance-based design guidelines for high-efficiency buildings.

2. Scope of the Study

Windows are composite systems composed of various materials, including glazing, spacers, and frames. Accordingly, multiple factors influence thermal bridging during window installation. One primary factor is the window frame, which is most commonly made of PVC or aluminum (ALU), though timber frames are also occasionally used. Additionally,

the frame geometry, which varies depending on the window's opening mechanism, can affect both the occurrence and severity of thermal bridging.

Another key factor is the type of glazing. The number of glass layers—such as double, triple, or quadruple glazing—as well as the application of low-emissivity (Low-E) coatings and inert gas fillings can significantly affect thermal performance. Moreover, the thermal characteristics of spacers, used to maintain spacing between the glass layers, also contribute to thermal bridge formation.

The difference between single- and double-window systems is also a critical consideration. In particular, double-sliding-window systems—comprising two independent sashes installed on separate tracks—have a larger contact area with the building structure than single-window systems, which may influence the installation-related thermal bridge characteristics.

While the above factors pertain to the window system itself, the characteristics of the building structure into which the window is installed also significantly influence thermal bridging. Structural materials and insulation strategies play a key role. For example, in concrete wall assemblies, the position of the insulation layer—whether external or internal—can substantially impact the extent of installation-related thermal bridges. In this study, the effects of thermal bridging were investigated for both externally insulated and internally insulated concrete wall assemblies.

This study specifically investigates the influence of window type (single- vs. double-window systems) on installation-related thermal bridges. To align with Korean construction practices and regulatory requirements, the analysis includes:

- A double-sliding-window system using quadruple glazing, composed of two separate double-glazed units;
- A single-window system with triple glazing.

Both configurations reflect the enhanced insulation performance standards currently applied in South Korea.

Since the thermal bridge at the installation interface is influenced by the window-to-structure contact area, comparing single- and double-window systems provides a basis for examining how this difference in contact area relates to installation-related thermal bridge characteristics. Additionally, the study examines the impact of installation position by evaluating three configurations—exterior, middle, and interior—for both externally and internally insulated concrete wall assemblies.

Point thermal bridges caused by mechanical brackets, along with the mitigation effect of the DIN 4108-2 insulation overlap detail for the applicable configurations, were also incorporated into the evaluation framework to provide a comprehensive assessment of installation-related thermal performance.

To isolate key variables, all other parameters were kept constant across comparative cases. PVC frames were used in all window models, and the same window specifications described above were applied consistently to both externally and internally insulated concrete wall assemblies.

3. Review of Standards Related to Thermal Bridges in Window Installations

3.1. ISO 10077

ISO 10077-1 [15] provides a method for calculating the thermal transmittance of windows (U-value), as expressed in Equation (1)

$$U_w = \frac{\sum U_g A_g + \sum U_f A_f + \sum \psi_g l_g}{\sum A_g + \sum A_f} \quad (1)$$

U_g is the thermal transmittance of glazing;
 A_g is the area of glazing;
 U_f is the thermal transmittance of the frame;
 A_f is the area of the frame;
 ψ_g is the linear thermal transmittance at the glazing edge;
 l_g is the length of the glazing edge.

This formula indicates that the overall thermal transmittance of a window system is obtained by combining the area-weighted contributions of the glazing and frame with the length-weighted contribution of the linear thermal bridge at the glazing edge.

ISO 10077-2 [16] complements this methodology by providing standardized values for interior and exterior surface thermal resistances, as summarized in Table 1. These values are essential for heat transfer simulations and vary depending on the component location. The standard distinguishes between general surface regions and edge zones, where reduced radiative and convective heat transfer results in increased surface resistance.

Table 1. Surface resistances for window profiles according to ISO 10077-2.

Position	External Rse	Internal Rsi
Normal (plane surface)	0.04	0.13
Reduced radiation/convection (in edges or junctions between two surfaces)	0.04	0.20

3.2. ISO 10211

ISO 10211 [17] provides a standardized methodology for evaluating thermal bridges in buildings, including the calculation of linear thermal transmittance, as defined in Equation (2):

$$\psi = L_{2D} - \sum U_j l_j \quad (2)$$

L_{2D} is the two-dimensional thermal coupling coefficient obtained through numerical heat transfer simulation. It represents the total heat flow per unit temperature difference (1 K) per unit length, expressed in W/m·K.

U_j is the one-dimensional thermal transmittance of the building components adjacent to the junction, in W/m²·K.

l_j is the length of each component with U-value U_j .

This equation quantifies the excess heat transfer at a junction beyond what would occur through adjacent planar elements alone.

In addition, ISO 10211 defines a method for calculating point thermal transmittance, which corresponds to three-dimensional thermal bridges commonly found in building details such as brackets or fasteners. This is expressed in Equation (3):

$$\chi = L_{3D} - \sum U_i A_i - \sum \psi_j l_j \quad (3)$$

L_{3D} is the three-dimensional thermal coupling coefficient, representing the total heat flow per unit temperature difference of 1 K, obtained from three-dimensional heat transfer simulations. It is expressed in W/K.

U_i denotes the one-dimensional thermal transmittance of the evaluated building components and is given in W/m²·K.

A_i refers to the surface area of each component associated with U_i , measured in m².

ψ_j is the linear thermal transmittance as defined in Equation (2), expressed in W/m·K.

l_j represents the length over which the linear thermal bridge ψ_j occurs, measured in m.

The point thermal transmittance χ is calculated by comparing the total simulated heat flow to the heat flow through the adjoining planar and linear elements, thereby isolating the additional heat loss attributed to point thermal bridges.

3.3. KIAEBS S-8:2017

The Korean Institute of Architectural Sustainable Environment and Building Systems (KIAEBS) has established a standard method [18] for evaluating the thermal performance of windows, explicitly incorporating the effects of installation-related thermal bridges. This method integrates the concepts of linear thermal transmittance and point thermal transmittance, as defined in ISO 10211, and proposes the calculation of the effective window U-value including installation thermal bridges, as expressed in Equation (4):

$$U_{w,install} = U_w + \frac{\sum \psi_i \cdot l_i + \sum \chi_j \cdot n_j}{A_w} \quad (4)$$

U_w is the nominal thermal transmittance of the window itself, calculated according to ISO 10077-1 (Equation (1)).

ψ_i is the linear thermal transmittance at the window installation interface, determined according to Equation (2).

l_i is the length over which the linear thermal bridge ψ_i occurs.

χ_j is the point thermal transmittance, representing the additional heat flow through point fixings such as brackets, derived according to Equation (3).

n_j is the number of point thermal bridges associated with χ_j .

A_w is the reference area of the window (glazing and frame combined).

This approach allows for a more accurate assessment of the real-world thermal performance of installed windows by incorporating both linear and point thermal bridge effects, which are often overlooked in conventional evaluations.

3.4. DIN 4108-2

DIN 4108-2 [19] provides design examples for addressing thermal bridges and offers guidelines for minimizing thermal bridging at window installations. Among these, design recommendations for externally insulated concrete wall assemblies are illustrated in Figure 1. Since DIN 4108-2 does not provide specific design guidelines for internally insulated concrete walls, the guideline-based overlap detail evaluation was limited to externally insulated configurations. For internally insulated walls, an interior reveal insulation return detail was evaluated instead (Section 5).

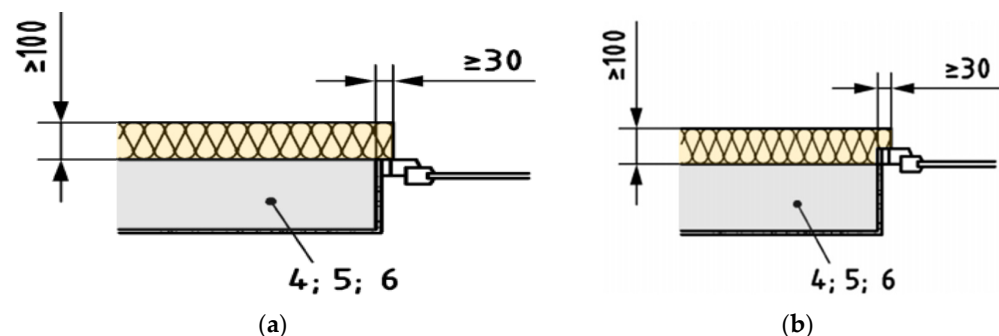


Figure 1. Design recommendations of DIN 4108-2 for window installation in externally insulated concrete walls: (a) window fixed to the concrete structure below the insulation layer ($\Psi \leq 0.18 \text{ W/m}\cdot\text{K}$); (b) window fixed within the insulation layer ($\Psi \leq 0.07 \text{ W/m}\cdot\text{K}$). In both cases, an insulation overlap of at least 30 mm over the frame is recommended.

Figure 1a presents the guideline for cases where the window is installed directly onto the concrete structure. It recommends applying an insulation overlap of at least 30 mm and achieving a linear thermal transmittance below 0.18 W/m·K at the installation interface.

Figure 1b presents the guideline for installations where the window is mounted onto the insulation layer itself. Similarly, a minimum 30 mm insulation overlap is recommended, with a target linear thermal transmittance below 0.07 W/m·K.

Additionally, point thermal bridges may arise from mechanical fixings used to secure the window frames; accordingly, such effects were also considered in the present evaluation alongside the DIN 4108-2 overlap detail assessment.

3.5. Design Standards for Condensation Prevention in Multi-Family Residential Buildings

In South Korea, performance standards [20] have been established to prevent condensation in multi-family residential buildings. These standards specify maximum Temperature Difference Ratio (TDR) criteria for key structural components. The TDR is defined as the ratio of the temperature difference between the indoor air and the interior surface at the area of interest to the temperature difference between the indoor and outdoor air and is calculated using Equation (5).

Internationally, instead of TDR, the surface temperature factor (f_{Rsi}) is typically used to assess condensation risk, and it can be calculated according to Equation (6). For international context, ISO 13788 [21] determines the minimum temperature factor $f_{Rsi,min}$ from the external climate and internal humidity conditions. DIN 4108-2 [19] specifies $f_{Rsi} \geq 0.70$ for opaque building elements, evaluated with an increased internal surface resistance ($R_{si} = 0.25 \text{ m}^2 \cdot \text{K/W}$). The Korean window frame threshold for Seoul ($\text{TDR} = 0.28$) corresponds to $f_{Rsi} = 0.72$.

When evaluating TDR, the indoor and outdoor temperature conditions are critical. For reference, the TDR evaluation criteria applicable to the Seoul region in South Korea are summarized in Table 2.

$$\text{TDR} = \frac{\theta_i - \theta_{si,min}}{\theta_i - \theta_e} \quad (5)$$

$$f_{Rsi} = \frac{\theta_{si,min} - \theta_e}{\theta_i - \theta_e} = 1 - \text{TDR} \quad (6)$$

Table 2. Performance Standards for Condensation Prevention in Seoul.

TDR	Outside Temperature	Indoor Temperature
0.28	−15 °C	25 °C

4. Linear Thermal Bridge and TDR Evaluation by Installation Position

4.1. Evaluation Method and Model

Simulations were conducted to evaluate the linear thermal bridges and Temperature Difference Ratio (TDR) at window installation interfaces. The analyses were performed using Flixo (flixo pro 8.0, infomind, Zürich, Switzerland), a two-dimensional steady-state heat transfer simulation software compliant with ISO 10211 and ISO 10077-2.

The boundary conditions applied during the simulations are summarized in Table 3. Surface thermal resistances were assigned according to the values specified in ISO 10077-2, while indoor and outdoor temperatures were set based on South Korean TDR evaluation standards applicable to the Seoul region. In accordance with ISO 10077-2, the reduced internal surface resistance ($R_{si} = 0.20 \text{ m}^2 \cdot \text{K/W}$) was applied to the interior frame surfaces in the corner region where the frame meets the glazing (yellow boundaries in Figure 2),

over a boundary length of approximately 29 mm for the single window and 3.8 mm for the double window; all other interior surfaces were assigned $R_{si} = 0.13 \text{ m}^2 \cdot \text{K}/\text{W}$.

Table 3. Boundary Conditions for External and Internal Surfaces.

Position	Temperature	Surface Resistance
External	-15°C	$0.04 \text{ m}^2 \cdot \text{K}/\text{W}$
Internal	25°C	$0.13 \text{ m}^2 \cdot \text{K}/\text{W}$

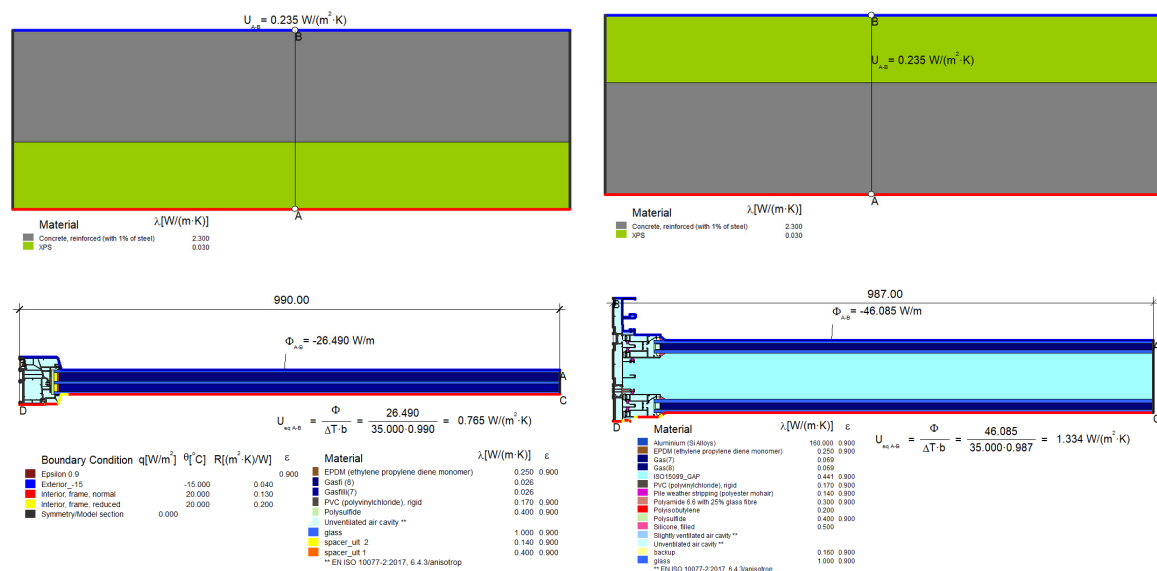


Figure 2. Thermal transmittance and material properties of single- and double-window systems, and externally/internally insulated concrete walls. Yellow boundaries indicate the reduced internal surface resistance ($R_{si} = 0.20 \text{ m}^2 \cdot \text{K}/\text{W}$). The window U-values shown were calculated with internal and external temperatures of 20°C and -15°C ($\Delta T = 35 \text{ K}$); because the models are linear, the U-values do not depend on the temperature difference and are identical under the boundary conditions of Table 3.

The thermal conductivities of the materials, as well as the thermal transmittance (U-values) of the single- and double-window systems and the external wall, are presented in Figure 2.

The U-value of the external wall was set to $0.235 \text{ W}/\text{m}^2 \cdot \text{K}$, meeting the standard requirement of $0.24 \text{ W}/\text{m}^2 \cdot \text{K}$ for Central Region 2 residential buildings under the Korean Building Energy Conservation Design Standards [22] (effective 8 August 2024). The opaque wall consists of 200 mm reinforced concrete ($\lambda = 2.3 \text{ W}/\text{m} \cdot \text{K}$, 1% steel) and 120 mm XPS insulation ($\lambda = 0.030 \text{ W}/\text{m} \cdot \text{K}$); the same layers were used for the externally and internally insulated walls, with the layer order reversed.

The glazing units were defined by their layer build-up and nominal center-of-glass U-value (U_g), and the gas cavities were assigned equivalent thermal conductivities reproducing these U_g values. The triple-glazed unit of the single-window system consists of 5/16/5/16/5 mm (glass/cavity/glass/cavity/glass) with $U_g = 0.718 \text{ W}/\text{m}^2 \cdot \text{K}$, the effects of Low-E coatings and gas filling being included in this value. Each double-glazed unit of the double-window system consists of 6/12/6 mm with $U_g = 2.81 \text{ W}/\text{m}^2 \cdot \text{K}$, a value typical of uncoated clear glass with an air-filled cavity.

For the single-window system, unventilated air cavities were modeled according to ISO 10077-2. As a result, the U-value of the single window was calculated to be $0.765 \text{ W}/\text{m}^2 \cdot \text{K}$, satisfying the maximum allowable U-value of $1.5 \text{ W}/\text{m}^2 \cdot \text{K}$ under the Korean standards.

For the double-window system, two insulating glass units (each with a U-value of approximately $2.810 \text{ W/m}^2\cdot\text{K}$) were assumed. The air cavity between the two units, with a thickness of 85 mm, was assigned thermal resistance values according to ISO 15099 [23]. Its thermal resistance, including natural convection and long-wave radiation, was $0.193 \text{ m}^2\cdot\text{K/W}$, and the cavity was represented in the model as an equivalent solid with a thermal conductivity of $0.441 \text{ W/m}\cdot\text{K}$.

Other cavities within the frame were modeled as unventilated air cavities according to ISO 10077-2, while cavities connected to the external environment through narrow slots were treated as slightly ventilated air cavities. Consequently, the overall U-value of the double-window system was calculated to be $1.334 \text{ W/m}^2\cdot\text{K}$, also meeting the national requirement of $1.5 \text{ W/m}^2\cdot\text{K}$.

4.2. Evaluation Results for Externally Insulated Concrete Wall Assemblies

The simulation results for single- and double-window systems installed at exterior, middle, and interior positions in externally insulated concrete wall assemblies are shown in Table 4. When comparing the overall average linear thermal transmittance values across the three installation positions, the single-window system exhibited significantly higher thermal bridging ($0.346 \text{ W/m}\cdot\text{K}$) than the double-window system ($0.065 \text{ W/m}\cdot\text{K}$). The exterior position was an exception to this trend, where the single-window system exhibited a lower Ψ -value than the double-window system.

Table 4. Linear thermal transmittance (Ψ [$\text{W/m}\cdot\text{K}$]) and Temperature Difference Ratio (TDR) for single- and double-window systems installed at exterior, middle, and interior positions in externally insulated concrete wall assemblies.

Installation Position	Single-Window System	Double-Window System
Exterior Installation		
Middle Installation		
Interior Installation		

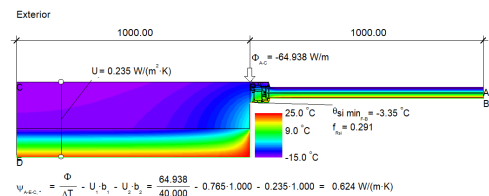
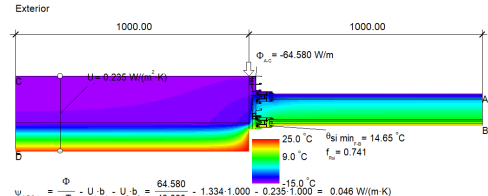
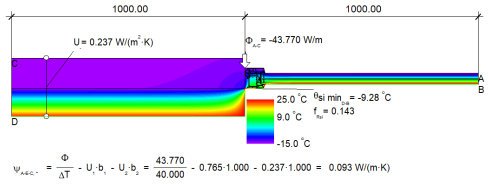
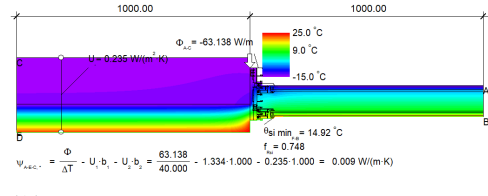
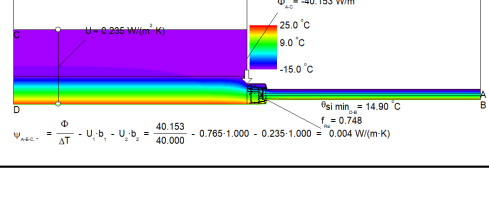
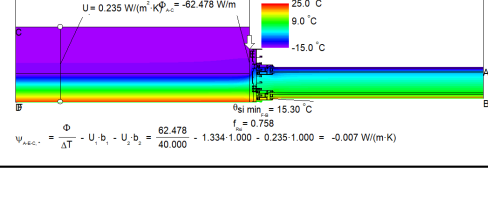
For both window types, the linear thermal bridge was smallest in the exterior position (average $0.014 \text{ W/m}\cdot\text{K}$), followed by the middle ($0.100 \text{ W/m}\cdot\text{K}$) and interior positions ($0.504 \text{ W/m}\cdot\text{K}$). This trend is consistent with the characteristics of externally insulated walls, where exterior-side installations place the window over the insulation layer, thereby maintaining thermal continuity, while interior installations place the window directly on the concrete substrate, creating thermal discontinuities.

Additionally, the Temperature Difference Ratio (TDR) was calculated using Equation (5), based on fRsi values obtained from the simulations. The results showed that the average TDR for the double-window system was 0.216, which is lower than that of the single-window system (0.286), indicating better condensation resistance. Notably, the interior installation of the single-window system exceeded the TDR criterion of 0.28 specified for window frame regions in the Seoul climate zone, suggesting a high risk of surface condensation in that configuration.

4.3. Evaluation Results for Internally Insulated Concrete Wall Assemblies

The simulation results for single- and double-window systems installed at exterior, middle, and interior positions in internally insulated concrete wall assemblies are presented in Table 5. When comparing the average linear thermal transmittance values, the single-window system exhibited significantly greater thermal bridging (0.240 W/m·K) than the double-window system (0.016 W/m·K).

Table 5. Linear thermal transmittance (Ψ [W/m·K]) and Temperature Difference Ratio (TDR) for single- and double-window systems installed at exterior, middle, and interior positions in internally insulated concrete wall assemblies.

Installation Position	Single-Window System	Double-Window System
Exterior Installation	 $U = 0.235 \text{ W/(m}^2\cdot\text{K)}$ $\Phi_{ext} = -64.938 \text{ W/m}$ $\theta_{si \text{ min}} = -3.35^\circ\text{C}$ $f_{rsi} = 0.291$ $\Psi_{ext} = \frac{\Phi}{\Delta T} = \frac{64.938}{40,000} = 0.00162 \text{ W/(m}\cdot\text{K)}$	 $U = 0.235 \text{ W/(m}^2\cdot\text{K)}$ $\Phi_{ext} = -64.580 \text{ W/m}$ $\theta_{si \text{ min}} = 14.65^\circ\text{C}$ $f_{rsi} = 0.741$ $\Psi_{ext} = \frac{\Phi}{\Delta T} = \frac{64.580}{40,000} = 0.00161 \text{ W/(m}\cdot\text{K)}$
Middle Installation	 $U = 0.237 \text{ W/(m}^2\cdot\text{K)}$ $\Phi_{ext} = -43.770 \text{ W/m}$ $\theta_{si \text{ min}} = -9.28^\circ\text{C}$ $f_{rsi} = 0.143$ $\Psi_{ext} = \frac{\Phi}{\Delta T} = \frac{43.770}{40,000} = 0.00109 \text{ W/(m}\cdot\text{K)}$	 $U = 0.235 \text{ W/(m}^2\cdot\text{K)}$ $\Phi_{ext} = -63.138 \text{ W/m}$ $\theta_{si \text{ min}} = 14.92^\circ\text{C}$ $f_{rsi} = 0.748$ $\Psi_{ext} = \frac{\Phi}{\Delta T} = \frac{63.138}{40,000} = 0.00158 \text{ W/(m}\cdot\text{K)}$
Interior Installation	 $U = 0.235 \text{ W/(m}^2\cdot\text{K)}$ $\Phi_{ext} = -40.153 \text{ W/m}$ $\theta_{si \text{ min}} = 14.90^\circ\text{C}$ $f_{rsi} = 0.748$ $\Psi_{ext} = \frac{\Phi}{\Delta T} = \frac{40.153}{40,000} = 0.00100 \text{ W/(m}\cdot\text{K)}$	 $U = 0.235 \text{ W/(m}^2\cdot\text{K)}$ $\Phi_{ext} = -62.478 \text{ W/m}$ $\theta_{si \text{ min}} = 15.30^\circ\text{C}$ $f_{rsi} = 0.758$ $\Psi_{ext} = \frac{\Phi}{\Delta T} = \frac{62.478}{40,000} = 0.00156 \text{ W/(m}\cdot\text{K)}$

For both window types, the linear thermal bridge was highest in the exterior installation (average 0.335 W/m·K), followed by the middle (0.051 W/m·K) and interior positions (−0.002 W/m·K). This trend is consistent with the characteristics of internally insulated walls, where interior-side installations place the window over the insulation layer, maintaining thermal continuity, while exterior installations place the window directly onto the concrete, interrupting the insulation.

TDR results revealed that the double-window system had a lower average value (0.251) compared to the single-window system (0.606), indicating better resistance to condensation. Notably, the TDR values for the exterior and middle installations of the single-window system exceeded the threshold of 0.28 established for the window frame region in Seoul's climate conditions, suggesting a high risk of surface condensation in these configurations.

4.4. Comprehensive Analysis

The simulation results for single- and double-window systems installed at exterior, middle, and interior positions in both externally and internally insulated concrete wall assemblies are summarized in Table 6. Among the evaluated configurations, the internally insulated cases exhibited a lower overall average linear thermal transmittance ($0.128 \text{ W/m}\cdot\text{K}$) than the externally insulated cases ($0.206 \text{ W/m}\cdot\text{K}$). This difference reflects the specific insulation continuity and window installation geometry examined in this study and should not be generalized as an inherent characteristic of internally insulated wall systems as a whole.

Table 6. Comparison of linear thermal transmittance (Ψ [$\text{W/m}\cdot\text{K}$]) and Temperature Difference Ratio (TDR) for single- and double-window systems installed at exterior, middle, and interior positions in externally and internally insulated concrete wall assemblies.

		Single-Window System		Double-Window System		Average
		Ψ [$\text{W/m}\cdot\text{K}$]	TDR [-]	Ψ [$\text{W/m}\cdot\text{K}$]	TDR [-]	Ψ [$\text{W/m}\cdot\text{K}$]
Externally Insulated Wall	Exterior	0.005	0.252	0.022	0.219	0.014
	Middle	0.145	0.239	0.054	0.215	0.100
	Interior	0.888	0.367	0.120	0.215	0.504
	Average	0.346	0.286	0.065	0.216	0.206
Internally Insulated Wall	Exterior	0.624	0.709	0.046	0.259	0.335
	Middle	0.093	0.857	0.009	0.252	0.051
	Interior	0.004	0.252	−0.007	0.242	−0.002
	Average	0.240	0.606	0.016	0.251	0.128

However, the TDR results revealed a different trend. Both single- and double-window systems showed higher TDR values in internally insulated walls, indicating a greater risk of surface condensation. This is due to the fact that, in internally insulated walls, the concrete substrate directly receives the cold outdoor temperature, resulting in lower interior surface temperatures near the window frame compared to externally insulated systems.

This decoupling arises because Ψ and TDR describe different quantities. Ψ integrates the additional heat flow along the entire junction, whereas TDR is governed by the single coldest point on the interior surface. In internally insulated walls, the concrete remains cold, and where the interior insulation terminates at the reveal, a small area of cold concrete is exposed near the frame. This area contributes little to the total heat flow, and hence to Ψ , but determines the minimum surface temperature. Consequently, Ψ alone is not sufficient to assess window installation details, and both Ψ and TDR should be evaluated.

Under steady-state conditions, the TDR is independent of the indoor and outdoor temperatures; the calculated values therefore apply to all climate regions, and only the threshold differs. For PVC window frames, the Korean standard [20] specifies thresholds of 0.25 for Central Region 1 (-20°C), 0.28 for Central Region 2 (-15°C , including Seoul) and 0.32 for the Southern Region (-10°C). In the Southern Region, the same three configurations as in Seoul (TDR = 0.367, 0.709 and 0.857) fail to meet the criterion, whereas in Central Region 1, four additional configurations with TDR values of 0.252–0.259 also fail. The criterion is met in all regions only by the double-window system in the externally insulated wall, the single window installed in the middle position of the externally insulated wall, and the double window installed on the interior side of the internally insulated wall.

In conclusion, while internally insulated concrete walls may exhibit lower linear thermal transmittance at the window interface, they are more vulnerable to condensation risk at the glazing edge. Therefore, despite the lower average installation Ψ -values observed in internally insulated walls, externally insulated assemblies provided more favorable overall

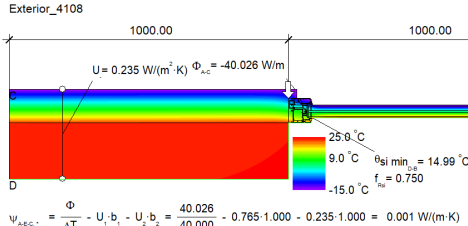
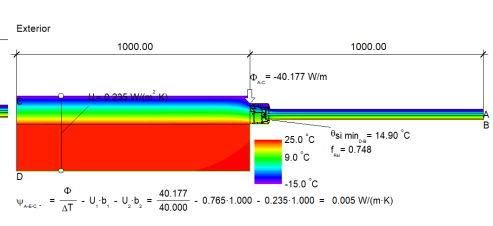
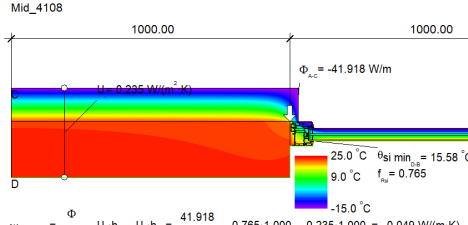
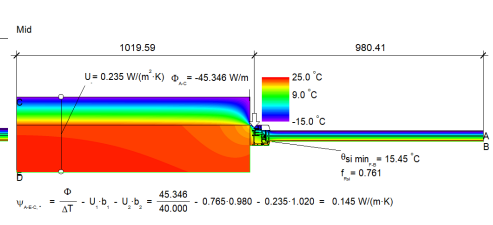
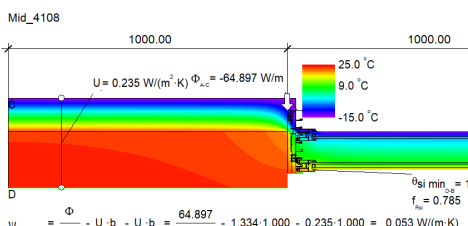
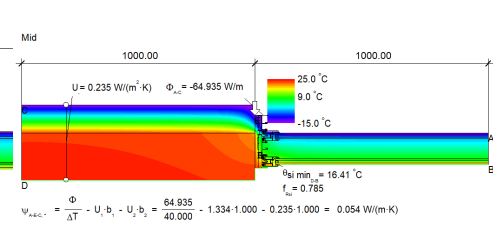
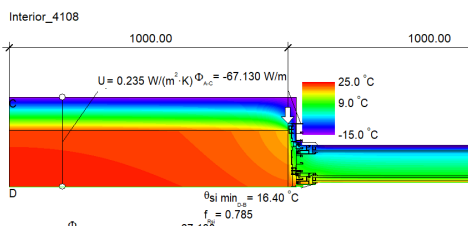
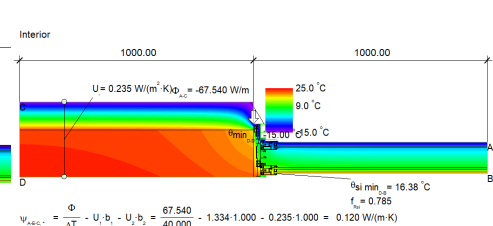
performance when both thermal continuity and condensation risk were considered. Among the evaluated configurations, exterior-side installation in externally insulated concrete walls demonstrated the best overall performance within the conditions of this study.

5. Evaluation of Linear Thermal Bridge Reduction Based on DIN 4108-2 Guidelines

To evaluate the effectiveness of DIN 4108-2 design recommendations, simulations were conducted to assess the impact of a 30 mm insulation overlap on the reduction in linear thermal bridges. Among the six configurations previously examined, four installation scenarios were selected where the guideline-compliant overlap detail could be realistically applied: (1) single window—exterior installation, (2) single window—middle installation, (3) double window—middle installation, and (4) double window—interior installation.

For all four cases, the application of DIN 4108-2 overlap details resulted in a reduction of varying magnitude in linear thermal transmittance compared to the base installation condition. In particular, the single window with middle installation exhibited a significant improvement, with the linear thermal transmittance (Ψ) reduced from 0.145 W/m·K to 0.049 W/m·K (Table 7).

Table 7. Comparison of Linear Thermal Transmittance (Ψ [W/m·K]) with and without DIN 4108-2 Insulation Overlap Guidelines.

Type	Guideline-Compliant Overlap Detail	Standard Detail
Single Window—Exterior Installation	Exterior_4108  $\Psi_{AEC} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{40.026}{40.000} - 0.765 \cdot 1.000 - 0.235 \cdot 1.000 = 0.001 \text{ W/(m·K)}$	Exterior  $\Psi_{AEC} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{40.177}{40.000} - 0.765 \cdot 1.000 - 0.235 \cdot 1.000 = 0.005 \text{ W/(m·K)}$
	Mid_4108  $\Psi_{AEC} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{41.918}{40.000} - 0.765 \cdot 1.000 - 0.235 \cdot 1.000 = 0.049 \text{ W/(m·K)}$	Mid  $\Psi_{AEC} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{45.346}{40.000} - 0.765 \cdot 0.980 - 0.235 \cdot 1.020 = 0.145 \text{ W/(m·K)}$
Double Window—Middle Installation	Mid_4108  $\Psi_{AEC} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{64.897}{40.000} - 1.334 \cdot 1.000 - 0.235 \cdot 1.000 = 0.053 \text{ W/(m·K)}$	Mid  $\Psi_{AEC} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{64.935}{40.000} - 1.334 \cdot 1.000 - 0.235 \cdot 1.000 = 0.054 \text{ W/(m·K)}$
Double Window—Interior Installation	Interior_4108  $\Psi_{AEC} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{67.130}{40.000} - 1.334 \cdot 1.000 - 0.235 \cdot 1.000 = 0.109 \text{ W/(m·K)}$	Interior  $\Psi_{AEC} = \frac{\Phi}{\Delta T} - U_1 \cdot b_1 - U_2 \cdot b_2 = \frac{67.540}{40.000} - 1.334 \cdot 1.000 - 0.235 \cdot 1.000 = 0.120 \text{ W/(m·K)}$

Because DIN 4108-2 provides no overlap detail for internally insulated walls, an interior reveal insulation return detail was additionally evaluated for these walls. In this detail, the interior insulation layer is continued along the window reveal up to the window frame with a thickness of 30 mm (Figure 3). The detail was applied to the two single-window configurations in the internally insulated wall that exceeded the TDR criterion, namely the exterior and middle installations.

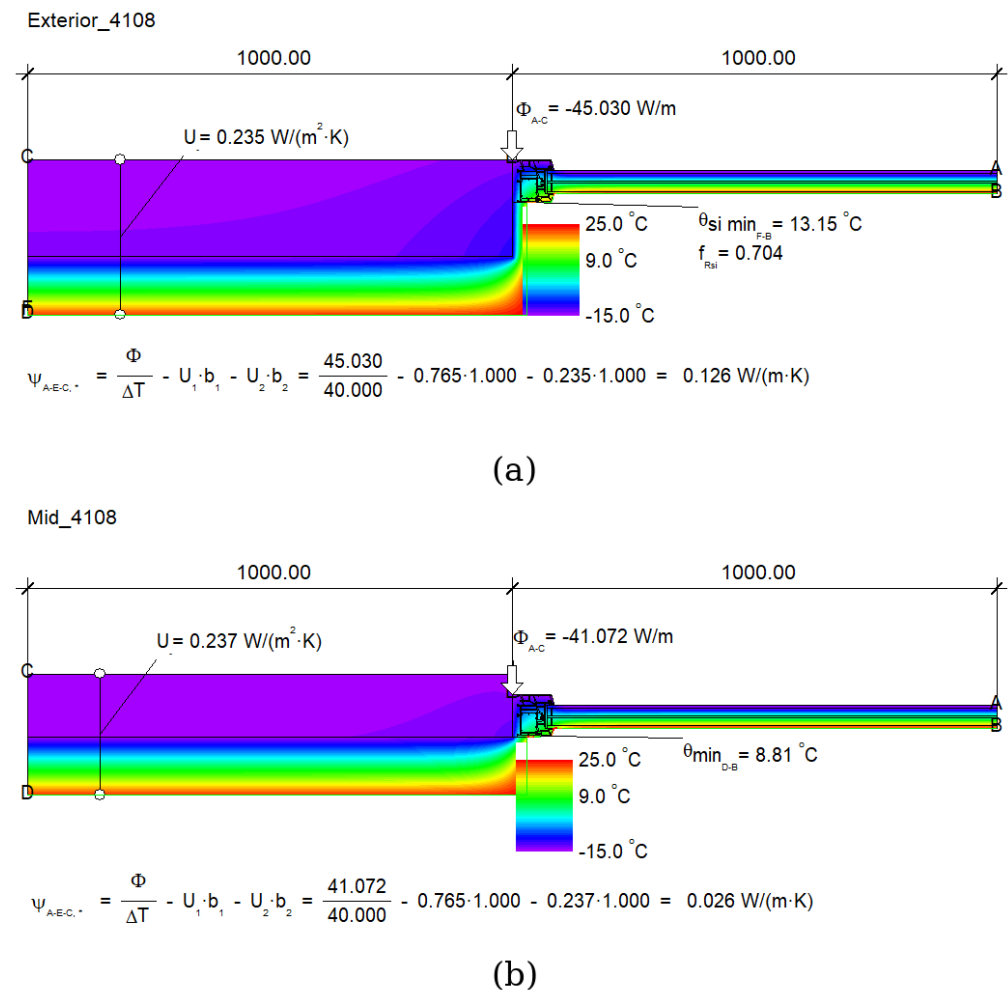


Figure 3. Interior reveal insulation return detail for the single-window system in internally insulated concrete walls: (a) exterior installation; (b) middle installation.

The reveal insulation return substantially reduced both the linear thermal bridge and the condensation risk. For the exterior installation, Ψ decreased from 0.624 to 0.126 W/m·K and the TDR from 0.709 to 0.296; for the middle installation, Ψ decreased from 0.093 to 0.026 W/m·K and the TDR from 0.857 to 0.405. However, both configurations still exceeded the TDR criterion of 0.28 for the Seoul region. These results indicate that, in internally insulated walls, a reveal insulation return substantially reduces both the thermal bridge and the condensation risk when the window is installed on the exterior side of or within the concrete layer, but that the 30 mm detail evaluated here is not sufficient on its own to meet the condensation criterion. Other variants, such as a thicker return or insulation materials with lower thermal conductivity, were not examined and may further improve the performance. Installing the window in line with the interior insulation layer (interior installation, TDR = 0.252) therefore remains the preferred option.

6. Evaluation of Point Thermal Bridges Due to Bracket Installation

6.1. Methodology

Point thermal bridges caused by metal brackets used for fixing window frames were analyzed using three-dimensional steady-state heat transfer simulations in TRISCO (version 14.0w, Physibel, Ghent, Belgium). The thermal conductivity of the brackets was set to 50 W/m·K, a representative value for carbon steel, following the design thermal value procedures of ISO 10456 [24]. All other material properties and boundary conditions were applied in accordance with the linear thermal bridge evaluation described earlier. Each three-dimensional calculation was iterated until the heat flow divergence of the total object fell below the convergence criterion of 0.001% (for example, 0.0002% for the single window in the middle position of the externally insulated wall). The bracket was modeled as an L-shaped carbon steel plate with a thickness of 4 mm, a width of 50 mm, and leg lengths of 40 mm (under the frame) and 50 mm (fixed to the face of the concrete), anchored with a steel anchor (shaft diameter 12 mm) embedded 40 mm into the concrete. For the calculation of $U_{w,install}$ (Equation (4)), a reference window of 2.0 m × 2.0 m ($A_w = 4.0 \text{ m}^2$, joint length 8.0 m) fixed with eight brackets (two per side) was assumed. The three-dimensional model extends 1.0 m along the installation joint with the bracket at its center and adiabatic boundaries at both ends, which corresponds to brackets repeated at 1.0 m intervals; this is consistent with the average bracket density of the reference window (eight brackets over 8.0 m of joint).

To derive the heat flow due to the bracket (Q_{3D} [W]), the difference in total heat flow between the model with the bracket and the model without the bracket was calculated. The resulting heat flow difference was divided by the assumed indoor–outdoor temperature difference (40 K) to obtain the point thermal transmittance (χ [W/K]).

6.2. Results

Table 8 presents the point thermal bridge simulation results for single- and double-window systems installed in externally and internally insulated concrete walls.

Among all configurations, the highest point thermal bridge was observed in the middle installation of the single-window system in the externally insulated wall (0.306 W, 0.008 W/K).

Additionally, relatively high levels of point heat flow were found in the interior-side installation of the double-window system in internally insulated walls (0.216 W, 0.005 W/K) and in the exterior-side installation of the double-window system in externally insulated walls (0.185 W, 0.005 W/K). These results indicate that the thermal impact of brackets can vary significantly depending on window type and installation position.

In contrast, negligible point thermal bridges were observed in the middle and interior installations of the double-window system in externally insulated walls, as well as in the exterior installation of the double-window system in internally insulated walls. These configurations demonstrated low vulnerability to bracket-induced thermal bridging.

These findings underscore that bracket-induced point thermal bridging can vary substantially depending on window type and installation position, highlighting the importance of considering bracket placement and thermal detailing during design and construction. The variation can be explained by the heat flow paths. The point thermal transmittance of a bracket is governed by the temperature difference between the materials that the highly conductive steel bracket connects. When the bracket penetrates the insulation layer to be anchored in the concrete, it bridges the large temperature difference across the insulation and forms a conductive bypass, whereas a bracket located entirely within the concrete connects regions of similar temperature and causes only a small χ . The highest value (0.008 W/K) occurred for the single window installed in the middle position of the exter-

nally insulated wall. In this configuration, the frame is set on the edge of the concrete, and the end of the bracket, which is fixed to the face of the concrete within the insulation layer, reaches the exterior reveal surface. The steel bracket therefore conducts heat from the warm concrete directly to the exterior surface, bypassing both the insulation and the frame. In the TRISCO results, the exposed end of the bracket remains at approximately 16.5 °C, close to the temperature of the concrete, and more than 90% of the additional heat flow caused by the bracket leaves through the exterior surface within approximately 20 mm of the bracket end, about half of it through the 4 mm × 50 mm end face of the bracket alone. As the bracket end was left uncovered in the model, this value represents a conservative case; a finishing layer covering the bracket end would reduce it somewhat.

Table 8. Point thermal transmittance (χ [W/K]) of brackets for exterior, middle, and interior installations of single- and double-window systems in externally and internally insulated concrete walls. $\chi = Q_{3D}/\Delta T$, where Q_{3D} is the difference in total heat flow between the models with and without the bracket and $\Delta T = 40$ K. The images show the calculated three-dimensional temperature distributions around the bracket (blue: low temperature; red: high temperature).

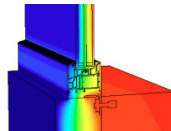
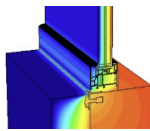
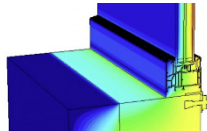
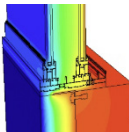
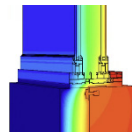
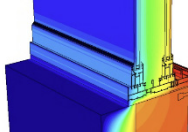
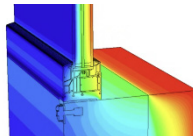
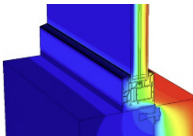
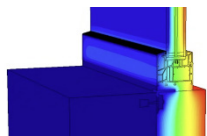
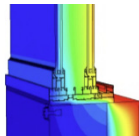
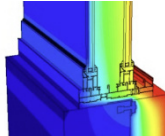
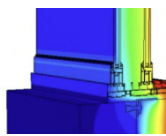
Type			Exterior Installation	Middle Installation	Interior Installation
Externally Insulated Wall	Single-Window System	Q_{3D}			
		χ	0.069 W 0.002 W/K	0.306 W 0.008 W/K	0.068 W 0.002 W/K
	Double-Window System	Q_{3D}			
		χ	0.185 W 0.005 W/K	0.010 W 0.000 W/K	0.006 W 0.000 W/K
Internally Insulated Wall	Single-Window System	Q_{3D}			
		χ	0.046 W 0.001 W/K	0.122 W 0.003 W/K	0.122 W 0.003 W/K
	Double-Window System	Q_{3D}			
		χ	0.000 W 0.000 W/K	0.041 W 0.001 W/K	0.216 W 0.005 W/K

Table 9 presents the results of point thermal bridge simulations for bracket installations under the DIN 4108-2 guideline, which recommends a 30 mm insulation overlap detail. The analysis was conducted for the four applicable configurations: exterior and middle installations for the single-window system, and middle and interior installations for the double-window system. For each case, the heat flow (Q_{3D} [W]) and point thermal transmittance (χ [W/K]) associated with the anchoring brackets were evaluated.

For the single-window system, the exterior installation exhibited the highest thermal loss, with Q_{3D} reaching 0.061 W and χ measuring 0.002 W/K. In contrast, the middle installation showed improved performance, with values of 0.027 W and 0.001 W/K, respectively.

The double-window system consistently exhibited low point thermal transmittance across all installation positions. Notably, the interior installation resulted in negligible thermal bridging, with both Q_{3D} and χ values measured at 0.000 W and 0.000 W/K, respectively.

Table 9. 3D simulation results of bracket-induced point thermal transmittance (χ) and heat flow (Q_{3D}) under DIN 4108-2-compliant insulation overlap details for single- and double-window systems. $\chi = Q_{3D}/\Delta T$, where Q_{3D} is the difference in total heat flow between the models with and without the bracket and $\Delta T = 40$ K.

Type		Exterior Installation	Middle Installation
Single-Window System	Q_{3D}	0.061 W	0.027 W
	χ	0.002 W/K	0.001 W/K
Type		Middle Installation	Interior Installation
Double-Window System	Q_{3D}	0.028 W	0.000 W
	χ	0.001 W/K	0.000 W/K

Comparing these results with the corresponding baseline cases without the overlap detail, the effect of the DIN 4108-2 guideline on point thermal transmittance varied by configuration. A clear reduction was observed for the single-window system at the middle installation position (from 0.008 W/K to 0.001 W/K). The single-window exterior installation remained unchanged at 0.002 W/K, and the double-window interior installation remained negligible at 0.000 W/K. For the double-window middle installation, point thermal transmittance changed slightly from 0.000 W/K to 0.001 W/K. These results indicate that the overlap detail's effect on bracket-induced point thermal transmittance was configuration-dependent rather than uniformly reductive. For the double-window middle installation, χ changed in unrounded terms from 0.00025 to 0.00070 W/K (Q_{3D} from 0.010 to 0.028 W). Because Q_{3D} is obtained as the difference between the total heat flows of the models with and without the bracket (68.476 W and 68.448 W for the case with the overlap), these values correspond to only approximately 0.015–0.04% of the total heat flow. The models with the bracket also require a much finer mesh than those without it (approximately 3.4 million versus fewer than 50,000 nodes), so a change of this size cannot be reliably distinguished from the effect of the different meshes and is not interpreted as a physical increase. The bracket-induced point thermal bridge of the double window in the middle position is therefore regarded as negligible both with and without the overlap, and its effect on $U_{w,install}$ is negligible.

Exterior installation within the insulation layer requires load-bearing support, typically provided by steel consoles or prefabricated installation systems made of high-density insulation. Although their structural design was outside the scope of this study, the results above show that steel fixings create point thermal bridges, particularly when the window is placed within the insulation layer. Thermally separated brackets or load-bearing insulating installation systems may be considered so that the thermal advantages of exterior installation are not offset by fastener heat losses; however, their effect on χ was not evaluated in this study and requires further verification, and their structural adequacy must be assessed separately.

7. Integrated Evaluation of Window U-Values ($U_{w,install}$) Including Installation Thermal Bridges

The effective thermal transmittance values ($U_{w,install}$) of single- and double-window systems, accounting for both linear and point thermal bridges, are summarized in Table 10. The evaluation encompassed externally and internally insulated concrete wall assemblies as well as installations incorporating DIN 4108-2 guideline-compliant insulation overlap details.

Table 10. Window U-values including installation thermal bridges ($U_{w,install}$) [$W/m^2 \cdot K$] for single- and double-window systems, evaluated for exterior, middle, and interior installation positions in externally and internally insulated concrete walls. Results also include configurations with DIN 4108-2 guideline-compliant overlap details.

$U_{w,install}$ [$W/m^2 \cdot K$]		Single-Window System	Double-Window System
Externally Insulated Wall	Exterior	0.778	1.387
	Middle	1.070	1.443
	Interior	2.544	1.574
	Average	1.464	1.468
Internally Insulated Wall	Exterior	2.015	1.426
	Middle	0.957	1.354
	Interior	0.779	1.331
	Average	1.250	1.370
Guideline-Compliant Overlap Detail [DIN 4108-2]	Exterior	0.771	-
	Middle	0.865	1.442
	Interior	-	1.552
	Average	0.818	1.497

For externally insulated concrete walls, single windows showed significant performance variation depending on the installation position. $U_{w,install}$ reached a maximum of $2.544 W/m^2 \cdot K$ for interior-side installations and a minimum of $0.778 W/m^2 \cdot K$ for exterior-side installations, with an average of $1.464 W/m^2 \cdot K$. Double windows exhibited a similar positional dependency, with $U_{w,install}$ ranging from $1.574 W/m^2 \cdot K$ (interior) to $1.387 W/m^2 \cdot K$ (exterior), yielding an average of $1.468 W/m^2 \cdot K$ —slightly higher than that of the single-window system.

In the case of internally insulated concrete walls, the average $U_{w,install}$ for the single-window system was $1.250 W/m^2 \cdot K$, a lower average $U_{w,install}$ than that of the externally insulated configuration. This was primarily due to the significantly reduced $U_{w,install}$ of $0.779 W/m^2 \cdot K$ observed for interior-side installation. The double-window system also maintained a comparable average $U_{w,install}$ of $1.370 W/m^2 \cdot K$ under internal insulation.

Notably, when the DIN 4108-2 guideline-compliant overlap detail—specifying at least 30 mm of insulation over the window frame—was applied, a general improvement in thermal performance was observed for the applicable configurations. The single-window system achieved an average $U_{w,install}$ of $0.818 W/m^2 \cdot K$ for the exterior and middle installation positions, representing an approximately 11.5% reduction compared with the same positions without the guideline-compliant overlap detail (average $0.924 W/m^2 \cdot K$). In particular, exterior installation under this guideline resulted in a $U_{w,install}$ of $0.771 W/m^2 \cdot K$, demonstrating the highest level of performance. For the double-window system, the average $U_{w,install}$ for the applicable middle and interior positions was $1.497 W/m^2 \cdot K$.

Based on Equation (4), the contribution of the installation thermal bridges, defined as $(U_{w,install} - U_w)/U_{w,install}$, ranged from 2% to 70% for the single-window system and was up to 15% for the double-window system, depending on the installation position and insulation strategy. Consequently, the ranking of the two window systems was reversed in two configurations: although the nominal U-value of the single window ($0.765 W/m^2 \cdot K$) is much lower than that of the double window ($1.334 W/m^2 \cdot K$), its effective U-value was

higher for interior installation in the externally insulated wall (2.544 vs. 1.574 W/m²·K) and for exterior installation in the internally insulated wall (2.015 vs. 1.426 W/m²·K). The linear thermal bridges dominated the installation effect, whereas the contribution of the point thermal bridges ($\Sigma\chi \cdot n / A_w$) was at most 0.016 W/m²·K. The share of the point thermal bridges in the installation-related increase became larger only where the linear thermal bridge was small, not because χ itself increased; for example, for the single window installed on the exterior side of the externally insulated wall, the brackets contributed 0.004 W/m²·K and the linear thermal bridge 0.010 W/m²·K, i.e., approximately 30% of the increase. These results show that the nominal window U-value alone is not a reliable indicator of the installed performance of a window.

In summary, the single-window system exhibited a high degree of sensitivity to installation position and insulation strategy, necessitating careful design and the implementation of thermal bridge mitigation measures. While the double-window system demonstrated relatively stable performance across configurations, interior-side installations still incurred increased thermal bridging. For configurations where the DIN 4108-2 overlap detail is applicable, applying this mitigation strategy is recommended to support consistent and energy-efficient window performance. Reducing installation-related thermal bridges complements other passive envelope measures, as the heat losses and low surface temperatures at window–wall junctions otherwise offset part of the benefit of high-performance windows and insulation. In particular, in the externally insulated wall, the effective U-value of the single window increased approximately 3.3-fold, from 0.765 to 2.544 W/m²·K, when installed on the interior side, and its TDR exceeded the threshold. For the wall and installation details analyzed in this study, high-performance single windows should therefore not be installed on the interior side of externally insulated walls, as the performance advantage of the window is largely lost through the installation.

8. Conclusions

This study investigated the thermal bridges associated with the installation of widely used single- and double-window systems in South Korea. Simulations were performed to evaluate linear thermal transmittance and Temperature Difference Ratio (TDR) for different installation positions—exterior, middle, and interior—within both externally and internally insulated concrete wall assemblies. The effects of bracket-induced point thermal bridges were also analyzed using three-dimensional heat transfer simulations. Effective window U-values ($U_{w,install}$) were calculated by integrating both linear and point thermal bridges to reflect realistic installation conditions.

For externally insulated concrete walls, exterior-side installation demonstrated the best overall thermal performance and lowest condensation risk, followed by middle and interior installations. In particular, the single-window system installed at the interior position exhibited a TDR value of 0.367, which exceeds the Korean condensation risk threshold of 0.28, indicating a high likelihood of surface condensation. Double-window systems showed generally lower TDR values, indicating more stable condensation resistance across installation positions.

In the case of internally insulated walls, the average linear thermal transmittance (0.128 W/m·K) was lower than that of the externally insulated counterparts (0.206 W/m·K). However, TDR values were higher in internally insulated walls, indicating a greater risk of condensation despite this lower average Ψ . An interior reveal insulation return reduced the TDR of the critical single-window configurations substantially (from 0.709 to 0.296 and from 0.857 to 0.405) but did not by itself satisfy the condensation criterion.

Three-dimensional analysis of point thermal bridges caused by metal brackets revealed significant variations depending on window type and installation position. The highest

point transmittance (0.008 W/K) occurred in single-window systems with mid-position installations in externally insulated walls. Conversely, the exterior-position double window in the internally insulated wall showed negligible point thermal bridging, whereas the interior-position configuration exhibited a relatively larger bracket-induced effect.

When the linear and point thermal bridges were combined, the resulting $U_{w,install}$ values demonstrated that although single windows have intrinsically better insulation performance (lower U-values), their performance deteriorates more significantly when installation-related thermal bridges are considered. This was particularly evident in interior installations, underscoring the necessity of thermally optimized design and detailing.

The application of DIN 4108-2 guidelines, which prescribe a 30 mm insulation overlap over the window frame, further improved thermal performance for the applicable configurations. The average $U_{w,install}$ for single windows at the exterior and middle positions improved by approximately 11.5% compared with the same positions under standard installation, with the largest improvement observed at the middle position. The effect of the overlap detail on point thermal bridging, however, varied depending on window type and installation position, as presented in Sections 5–7.

In summary, the thermal performance of window systems varies considerably based on window type, installation position, insulation strategy, and anchoring details. Within the conditions of this study (concrete walls with the investigated window types and the Korean climatic design conditions), exterior-side installation over the insulation layer in externally insulated walls is recommended for reducing heat loss and condensation risk. As thermal bridge behavior depends on the wall system, window type, and climatic conditions, this finding should not be generalized without further analysis. Additional thermal enhancements are particularly necessary for single-window systems. Although double windows offer more stable performance, attention should be paid to interior installations where bridging effects may increase. In particular, in the externally insulated wall, the effective U-value of the single window increased approximately 3.3-fold, from 0.765 to $2.544 \text{ W/m}^2\cdot\text{K}$, when installed on the interior side, and its TDR exceeded the threshold. For the wall and installation details analyzed in this study, high-performance single windows should therefore not be installed on the interior side of externally insulated walls, as the performance advantage of the window is largely lost through the installation.

The numerical models developed in this study were not independently validated against experimental measurements, benchmark cases, or previously published numerical results. Although the simulations followed the procedures specified in ISO 10211 and ISO 10077-2, further validation is required to assess the accuracy of the predicted thermal bridge effects under practical installation conditions. The numerical models assume perfect contact between materials. In practice, voids in the polyurethane foam, degraded perimeter seals, and alignment tolerances can create gaps and air paths at the frame-to-wall joint, causing convective heat losses and lower surface temperatures that are not captured by conductive steady-state models. The results should therefore be regarded as representing properly executed installations. In addition, air infiltration through the tracks of double sliding windows can bring cold air into the frame cavities and the cavity between the sashes, so the actual thermal bridge effects and condensation risk may exceed the simulated values. Furthermore, all models used PVC frames. Thermally broken aluminum frames differ from PVC frames in material and section design, and the highly conductive aluminum profiles may affect the heat flow at the joint and the interior surface temperatures near the frame. The direction and magnitude of these effects depend on the frame section and thermal break design, so the Ψ and TDR values obtained here cannot be transferred directly to aluminum frames.

Future studies should extend this analysis to other structural systems, such as steel or timber frames, and validate the simulation results through laboratory testing or field measurements. This study contributes meaningful insights for the development of high-efficiency, condensation-resistant window installation guidelines suitable for Korean building practices.

Author Contributions: Conceptualization, S.L. and M.J.; methodology, S.L.; software, S.L. and M.J.; validation, S.L. and M.J.; formal analysis, S.L.; investigation, S.L. and M.J.; writing—original draft preparation, S.L.; writing—review and editing, S.L. and M.J.; visualization, S.L.; supervision, M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable. This study did not involve humans or animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: During the preparation of this manuscript, the authors used Claude 2.1.303 (Anthropic) to assist with language editing, structural formatting, and reference formatting in accordance with the journal's template. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

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