Influence of Thermal Bridges on the Insulation Performance of Curtain Wall Panel Systems

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Abstract

Thermal insulation plays a key role in saving energy consumed by buildings. To obtain a high level of insulation performance, repeated thermal bridges should be minimized. These bridges may cause a substantial heat loss through the building envelope. Recently, the application of curtain walls has been rapidly increasing. However, thermal bridges frequently occur in the non-vision panel system in which the insulation materials are installed because of the numerous metal members passing through the insulation layer. The aim of this study was to analyze the influence of thermal bridges on the insulation performance of curtain wall panels in terms of the energy performance and internal surface condensation risk. A three-dimensional steady state heat transfer simulation was performed for four types of panel systems: insulation-joined metal sheet, insulation-separated metal sheet, bracket-fixed metal panel and screw-fixed metal panel. The heat loss, effective U-value, lowest internal surface temperature and lowest temperature factor of each panel system with and without thermal bridges were calculated and compared.

Keywords: curtain wall; panel system; thermal bridge; energy performance; internal surface condensation risk

1. Introduction

The Korean government has implemented various policies to reduce the annual building energy consumption by 60% compared to 2009 levels by 2017 and make zero energy consumption mandatory by 2025 (MOLIT, 2009). The core of the policy is a drastic strengthening of building insulation regulations; similar measures have also been taken in many other countries. It means that thermal insulation plays a key role in saving energy consumed by buildings. In practice, ensuring a high level of insulation performance requires the elimination of thermal bridges in the building envelope that reduce the local thermal resistance (Song et al., 2011).

The increasing trend of high-rise buildings has rapidly increased the spread of curtain wall systems that facilitate convenient installment, a shortened construction period, and free facade composition. Recently, curtain walls have been generally applied to not only high-rise commercial buildings but also high-rise residential buildings and mid- to low-rise commercial buildings. Although curtain walls have many advantages as noted above, joints between members are inevitable because metal members of different sizes are assembled, and highly thermally conductive metal is used in the main structural members. Many metal members for fixing curtain walls, such as trusses and fixing units, are also frequently installed to pass through the insulation layer. The center part of an individual unit in a curtain wall non-vision panel system with insulation materials has the required U-value. Nonetheless, local thermal bridges occur around the center which decrease the actual insulation performance. When evaluating the insulation performance in the code for building insulation design, the U-value of a building envelope is calculated without considering thermal bridges (MOLIT, 2013). Therefore, the designed insulation performance is not ensured in practice.

In this study, a three-dimensional heat transfer simulation was conducted on various types of curtain wall non-vision panel systems to examine the influence of multiple thermal bridges, such as trusses, fixing units, and joints between panels. The overall insulation performance in terms of the energy performance and internal surface condensation risk, and the effects of thermal bridges were quantitatively evaluated.

2. Components and Construction of the Curtain Wall Panel System

As illustrated in Fig.1., curtain walls are mainly classified into aluminum frame type and steel back truss type according to the installation method of
structural members. Aluminum frame curtain wall is installed by fixing mullions to floor slabs, and panels and glazings are installed between the mullions and transoms; the mullions and transoms tend to be exposed to the indoor and outdoor areas. Steel back truss curtain wall is installed by fixing grid-pattern steel trusses to floor slabs, and panels and glazings are fixed to the trusses; the trusses are hidden and not exposed to the indoor and outdoor areas. Existing researches for thermal performance of curtain walls mainly dealt with the mullions and transoms with glazings of the aluminum frame curtain wall (Song et al., 2013, No and Kim, 2005).

However, researches for overall insulation performance of the non-vision panel systems for the steel back truss curtain wall which is more widely applied because of lower construction costs, were rarely conducted. Therefore, this study focused on the panel systems of the steel back truss curtain wall. Components and construction of the steel back truss curtain wall were described in this section.

2.1 Components of the Steel Back Truss Curtain Wall Panel System

The steel back truss curtain wall panel system consists of interior and exterior materials, insulation, and trusses, as shown in Fig.2. Plaster boards are frequently used as interior materials and generally installed between floor-to-floor slabs. Combinations of exterior and insulation materials are often classified into sheet and metal panel types. In the sheet type, insulation materials are closely installed to exterior materials by being placed in empty spaces between the vertical or horizontal trusses after the exterior materials such as thin metal sheet and stone are fixed to the external side of trusses (insulation-joined sheet type; see Fig.2. and Fig.3.). Alternatively, they are installed between floor-to-floor slabs detached from exterior materials (insulation-separated sheet type; see Fig.2.). In the metal panel type, an insulation-embedded metal panel is fabricated by covering six faces of insulation materials with thin metal sheet, and then it is fixed to the external side of trusses (see Fig.2.).

In the insulation-joined sheet type, the trusses serve as major thermal bridges passing through the insulation layer because the trusses are located in the insulation layer and any additional insulation is mostly not provided. In the insulation-separated sheet type, the floor slabs serve as major thermal bridges passing through the insulation layer because the insulation materials are not continuous over the floor slabs located in the insulation layer. In the metal panel type, the trusses are not major thermal bridges because the trusses are detached from the insulation layer. However, both the vertical and horizontal joints
EN 13947 proposes a method for calculating the two- and three-dimensional heat transfer simulations. This standard also proposes methods and conditions of thermal bridges such as joints between panels and point thermal bridges passing through the insulation layer because all sides of the metal panel are covered with metal sheet.

A unit of the steel back truss curtain wall panel system can be produced with various sizes depending on the building facade design. The general height and width for the panel system unit are as follows: 600–1000 mm × 1500–2000 mm for metal sheet type; and 1000 mm × 2000–3000 mm for metal panel type.

2.2 Construction of the Steel Back Truss Curtain Wall Panel System

Anchor bolts or embedded channels are applied to fix the truss to the floor slab. With the former method, as shown in Fig.4.(a), an L-shaped bracket is fixed to the side or upper surface of the floor slab by an anchor bolt, and the bracket and truss are fixed by welding. For the sheet type, a Z-shaped folded edge of an exterior metal sheet is normally fixed to the truss with a screw, as shown in Fig.4.(b). As shown in Fig.4.(c), the metal panel is generally fixed to the truss through the insertion of its upper and bottom parts into an H-shaped bracket. As shown in Fig.4.(d), the upper part of the panel can also be fixed to the truss with a screw. These fixing units comprise metal with high thermal conductivities such as aluminum and steel. These units are installed at repeated intervals and serve as thermal bridges that are also connected to major thermal bridges passing through the insulation layer.

3. Evaluation Method of the Influence of Thermal Bridges on the Insulation Performance of Curtain Wall Panel System

3.1 Evaluation Overview

Standards for calculating the insulation performance of building envelopes when considering the effects of thermal bridges include ISO 10211 (ISO, 2007; Koo et al., 2011) and EN 13947 (European Standards, 2006; Kim and Yim, 2012). ISO 10211 defines a linear thermal bridge, which exhibits two-dimensional heat transfer in the building envelope, and a point thermal bridge, which exhibits three-dimensional heat transfer. This standard also proposes methods and conditions for calculating the linear thermal transmittance through a linear thermal bridge, and the point thermal transmittance through a point thermal bridge using two- and three-dimensional heat transfer simulations. EN 13947 proposes a method for calculating the U-value of a curtain wall using single or component assessment methods that reflect the linear thermal transmittance of each member joint. This method is relatively complicated because the areas, lengths, and thermal transmittances of both non-thermal bridges and thermal bridges should be calculated.

The purpose of this study was to evaluate the overall insulation performance including all thermal bridges, not to identify the individual effects of linear thermal bridges such as joints between panels and point thermal bridges such as fixing units. Therefore, the three-dimensional heat transfer simulation was conducted on a case including every thermal bridge (Case 1) and another case assuming the absence of thermal bridges (Case 2) as in the code for building insulation design. The results were compared to assess the reduction in insulation performance of the curtain wall panel system because of thermal bridges.

3.2 Evaluated Panel Systems and Simulation Models

The following four panel system types were evaluated: 1) insulation-joined and 2) -separated metal sheets and 3) bracket- and 4) screw-fixed metal panels. Fig.5. shows the elevations, plans, and sections of the evaluated panel systems based on the actual construction drawing of an office building with a 4m floor height. In accordance with construction practices, the metal sheet type had vertical and horizontal trusses, and the metal panel type had vertical trusses. The section sizes of the trusses were also set to be identical to those used in construction.

Table 1. lists the materials and U-values of panel systems at the center of the unit without thermal bridges. The U-values were set to be 0.270 W/m²K or less as required for the external walls, defined in the code for building insulation design.

Fig.6. shows the simulation model of Case 1 for the bracket-fixed metal panel system. Elements without significant impact on the insulation performance, such as the I-beam and ceiling hanger beneath the slab, were not modeled. The size of this model was decided to reflect the modeling principles of thermal bridges as proposed in ISO 10211 (ISO, 2007) and BR 497 (BRE, 2007). This model included a floor slab, by which the truss was fixed, and the center of the panel system unit was set to be a cutting plane to contain all of the repeated elements. The internal and external surface areas of each simulation model were set to be identical to facilitate a comparison of each panel system.
Fig. 5. Drawings of the Evaluated Panel Systems

(a) Metal sheet type

(b) Metal panel type
The simulation model of Case 2 was based on the center of the panel system unit, in which a one-dimensional heat transfer occurred. The size of this model was set to be identical to the external surface area of the Case 1 simulation model.

### 3.3 Simulation Conditions

Physibel Trisco 12.0 (2007) was used for the simulation. Physibel Trisco is a multi-purpose commercial program that simulates three-dimensional steady state heat transfers based on the finite difference method. Table 2. and 3. present the material properties and boundary conditions used in the simulation. The material properties were taken from the Guideline of the Code for Energy-efficient Building Design (KEMC, 2011). The indoor and outdoor temperatures and surface heat transfer coefficients were taken from the Code for Energy-efficient Building Design (MOLIT, 2013). Calculation parameters and number of nodes are shown in Table 4. and Table 5., respectively.

### 3.4 Insulation Performance Index for the Evaluation

The insulation performance of Case 1 and 2 were compared with regard to the energy performance and internal surface condensation risk. The energy performance was evaluated according to the total heat loss obtained through the heat transfer simulation and the effective U-value ($U_{\text{eff}}$), which was calculated with Eq. (1).

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### Table 1. Materials and U-values of the Evaluated Panel Systems at the Center of the Unit Without Thermal Bridges

| Material (Outside) | Insulation-joined metal sheet | Insulation-separated metal sheet | Bracket-fixed metal panel | Screw-fixed metal panel |
|--------------------|-------------------------------|----------------------------------|---------------------------|-------------------------|
| Aluminum sheet 3mm | Glass wool 115mm | Air gap 84.6mm | 2-ply Gypsum board | 25mm (Inside) |
| Glass wool 115mm | Air gap 155mm | Glass wool 115mm | 2-ply Gypsum board | 25mm (Inside) |
| Air gap 84.6mm | Glass wool 115mm | Glass wool 0.5mm | 2-ply Gypsum board | 25mm (Inside) |
| 2-ply Gypsum board | 25mm (Inside) | Air gap 185.6mm | 2-ply Gypsum board | 25mm (Inside) |
| 25mm (Inside) | 25mm (Inside) | Air gap 182.6mm | 2-ply Gypsum board | 25mm (Inside) |

U-value: 0.266 W/m²K

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### Table 2. Material Properties

| Material | Thermal conductivity (W/mK) | Emissivity |
|----------|-----------------------------|------------|
| Concrete | 1.600 | 0.90 |
| Gypsum board | 0.180 | 0.90 |
| Glass wool | 0.034 | 0.90 |
| Fire retarder | 45.0 | 0.25 |
| Insulation | 0.034 | 0.90 |
| Paint | 0.260 | 0.90 |
| Ceiling (gypsum board) | 0.180 | 0.90 |
| Floor covering (linoleum) | 0.170 | 0.90 |
| Steel sheet, steel truss | 45.0 | 0.25 |
| Aluminum sheet | 200.0 | 0.12 |
| Panel joint | Aluminum mold | 200.0 | 0.12 |
| Azon | 0.193 | 0.90 |
| EPDM | 0.250 | 0.90 |
| Silicon sealant | 0.350 | 0.90 |
| Back-up rod | 0.050 | 0.90 |
| (Polyurethane foam) | |
| Fixing unit | L-bracket | 45.0 | 0.25 |
| Aluminum bracket | 200.0 | 0.12 |
| Bolt, screw, washer, nut | 45.0 | 0.25 |

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### Table 3. Boundary Conditions

| Temperature (ºC) | Surface heat transfer coefficient (W/m²K) |
|------------------|------------------------------------------|
| Outdoor -11.3    | 23.25                                    |
| Indoor 20.0      | 9.09                                     |

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### Table 4. Calculation Parameters

| Maximum parameter | Value |
|-------------------|-------|
| Number of iteration cycles | 5 |
| Number of iterations within each iteration cycle | 10,000 |
| Temperature difference within each iteration cycle | 0.0001ºC |
| Temperature difference between iteration cycles | 0.001ºC |
| Heat flow divergence for total object | 0.001% |
| Heat flow divergence for any node | 1% |

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### Table 5. Number of Nodes in Simulation Models

| Type of panel system | Case 1 | Case 2 |
|----------------------|--------|--------|
| Insulation-joined metal sheet | 1,515,096 | 121,032 |
| Insulation-separated metal sheet | 1,559,844 | 164,000 |
| Bracket-fixed metal panel | 2,655,031 | 171,462 |
| Screw-fixed metal panel | 2,251,218 | 171,462 |

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The simulation model of Case 2 was based on the center of the panel system unit, in which a one-dimensional heat transfer occurred. The size of this model was set to be identical to the external surface area of the Case 1 simulation model.

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### 3.4 Insulation Performance Index for the Evaluation

The insulation performance of Case 1 and 2 were compared with regard to the energy performance and internal surface condensation risk. The energy performance was evaluated according to the total heat loss obtained through the heat transfer simulation and the effective U-value ($U_{\text{eff}}$), which was calculated with Eq. (1).
The internal surface condensation risk was evaluated using the lowest temperature factor \( f_{\text{RI},\text{ min}} \) (ISO, 2007), which was obtained with Eq. (2).

The temperature factor is a dimensionless number, and the risk of condensation decreases as it increases. When the temperature factor is identified, it is easy to determine whether the internal surface condensation occurs under various conditions through the use of a graph, as shown in Fig.7. For example, when the indoor temperature is 20 °C, the indoor humidity is 50%, and the outdoor temperature is -11.3 °C; \( f_{\text{RI}, \text{ min}} \) should be over 0.66 to prevent internal surface condensation (point A). In other words, when the indoor temperature is 20 °C, the outdoor temperature is -15 °C, and the \( f_{\text{RI}, \text{ min}} \) is 0.60; the indoor humidity should be 40% or less to prevent condensation (point B). After \( f_{\text{RI}, \text{ min}} \) obtained through the method above, the maximum allowable indoor humidity (\( \text{RH}_{\text{max}} \)) to prevent internal surface condensation was calculated for when the indoor temperature is 20 °C and the outdoor temperature is -11.3 °C.

\[
U_{\text{eff}} = \frac{q_{\text{tot}}}{A_e \times (T_i - T_o)} \tag{1}
\]

\[
f_{\text{RI}, \text{ min}} = \frac{T_{\text{sl, min}} - T_o}{T_i - T_o} \tag{2}
\]

Here, \( U_{\text{eff}} \): effective U-value (W/m²K)
\( q_{\text{tot}} \): total heat loss (W)
\( A_e \): external surface area (m²)
\( T_i \): indoor air temperature (°C)
\( T_o \): outdoor air temperature (°C)
\( f_{\text{RI}, \text{ min}} \): lowest temperature factor
\( T_{\text{sl, min}} \): lowest internal surface temperature (°C)

4. Evaluation Results
4.1 Energy Performance

Table 6 presents the energy performance of Case 1 and 2 for each panel system. For Case 1, the insulation-joined metal sheet showed the highest heat loss \( q_{\text{tot}} \) followed by the bracket-fixed metal panel, screw-fixed metal panel, and insulation-separated metal sheet. The insulation-joined metal sheet panel system showed the highest \( q_{\text{tot}} \) value because all of the vertical and horizontal trusses passing through the insulation layer served as thermal bridges. By contrast, the insulation-separated metal sheet panel system had the lowest \( q_{\text{tot}} \) value because the floor slab penetrating the insulation layer served as the only thermal bridge. Thus, the energy performance of a metal sheet panel system can be improved by selecting the insulation-separated type rather than the insulation-joined type. The bracket-fixed metal panel system had a slightly higher \( q_{\text{tot}} \) value than the screw-fixed metal panel system because of the additional metal brackets.

Fig.7. Temperature Factor and Outdoor Air Temperature at which Internal Surface Condensation Begins (\( T_i = 20^\circ \mathrm{C} \))

The effective U-value of Case 1 was 146%–219% higher for all panel systems than that of Case 2. This verified that the designed insulation performance cannot be ensured when the insulation performance of the curtain wall panel system is evaluated using the U-value calculated under the assumption that thermal bridges do not exist, as required by the code for building insulation design. Thus, the code should be improved to solve this problem. In particular, ASHRAE Standard 90.1-2013 (ASHRAE, 2013), which is the code for building insulation design in the US, can be taken as a reference. According to this standard, external walls are classified into mass, metal building, and steel framed types, and the external walls of the metal building and steel framed types must ensure much higher insulation performances than those of the mass type to prevent the decreasing energy performance because of thermal bridges. In addition, thermal breaking materials and systems which can be inserted between the metal members or can cover the whole metal parts need to be developed along with insulation details in order to eliminate thermal bridges.

4.2 Internal Surface Condensation Risk

Table 6 presents the evaluation results for the internal surface condensation risk of Case 1 and 2. In Case 1, the lowest internal surface temperature \( T_{\text{si, min}} \) occurred at the bottom of the upper plaster board in all of the panel systems. The insulation-separated metal sheet panel system showed the lowest \( T_{\text{si, min}} \). It was high in the insulation-joined metal sheet, screw-fixed metal panel, and bracket-fixed metal panel systems, in ascending order. Although the insulation-separated metal sheet showed the lowest \( q_{\text{tot}} \) value, the \( T_{\text{si, min}} \) value was the lowest because its thermal bridges were closest to the indoor space. The bracket- and screw-fixed metal panel systems showed \( T_{\text{si, min}} \) values of 15.5 and 15.3 °C, respectively, which were satisfactory. The lowest temperature factor \( f_{\text{RI, min}} \) for all Case 1 panel systems was between 0.64 and 0.86, and the maximum allowable indoor humidity (\( \text{RH}_{\text{max}} \)) to prevent internal surface condensation was between 48% and 75% when the indoor and outdoor temperatures were 20 and -11.3 °C, respectively.
Table 6. Insulation Performance Evaluation Results

| Insulation type | Case 1 | Case 2 | Case 1 | Case 2 |
|-----------------|--------|--------|--------|--------|
| Insulation-jointed metal sheet | Insulation-separatet metal sheet |
| q_{tot} (W) | 162.9 (+111.8) | 51.1 | 125.4 (+74.3) | 51.1 |
| U_{eff} (W/m²K) | 0.848 (+218.8%) | 0.266 | 0.653 (+145.5%) | 0.266 |
| T_{min, tot} (°C) | 11.8 (-7.3) | 19.1 | 8.7 (-10.4) | 19.1 |
| f_{t,i, min} | 0.74 (-0.23) | 0.97 | 0.64 (-0.33) | 0.97 |
| RH_{max, tot} (%) | 59 (-35) | 94 | 48 (-46) | 94 |

Bracket-fixed metal panel

Table 7. Insulation Performance Evaluation Results

| Insulation type | Case 1 | Case 2 |
|-----------------|--------|--------|
| q_{tot} (W) | 131.5 (+80.4) | 51.1 | 129.3 (+78.2) | 51.1 |
| U_{eff} (W/m²K) | 0.685 (+157.5%) | 0.266 | 0.673 (+153.0%) | 0.266 |
| T_{min, tot} (°C) | 15.5 (-3.6) | 19.1 | 15.3 (-3.8) | 19.1 |
| f_{t,i, min} | 0.86 (-0.11) | 0.97 | 0.85 (-0.12) | 0.97 |
| RH_{max} (%) | 75 (-19) | 94 | 74 (-20) | 94 |

The ( ) value represents the degree of increment compared with Case 2.

The internal surface condensation risk is generally higher in windows and doors than in the non-vision panel system. The United Kingdom (DCLG, 2013) and Netherlands (Dutch Building Code Online, 2012) require the f_{t,i, min} value of 0.5 for newly constructed office buildings. Regarding this value, the f_{t,i, min} values of Case 1 are reasonable; not at a serious risk level. However, f_{t,i, min} and RH_{max} of Case 2 were 0.97 and 94%, this means the thermal bridges significantly increased the internal surface condensation risk.

5. Summary and Conclusions

This study examined various types of curtain wall non-vision panel systems to evaluate the influence of thermal bridges on the overall insulation performance through three-dimensional heat transfer simulations in terms of the energy performance and internal surface condensation risk. The conclusions of this study were as follows:

(1) In Case 1, the insulation-jointed metal sheet panel system showed the highest heat loss followed by the bracket-fixed metal panel, screw-fixed metal panel, and insulation-separated metal sheet panel systems. Thus, for metal sheet panel systems, the insulation-separated type is more energy-efficient than the insulation-jointed type.

(2) The effective U-value of Case 1 was 146%–219% higher in all panel systems than that of Case 2. This verified that the designed insulation performance cannot be ensured when the curtain wall panel system is evaluated using the U-value calculated under the assumption that thermal bridges do not exist, as is stated in the code for building insulation design.
(3) The lowest internal surface temperature ($T_{\text{si,min}}$) in Case 1 occurred at the bottom of the upper plaster board in all of the panel systems. $T_{\text{si,min}}$ was the lowest in the insulation-separated metal sheet panel system but was high in the insulation-joined metal sheet, screw-fixed metal panel, and bracket-fixed metal panel systems.

(4) The lowest temperature factor ($f_{\text{Rsi,min}}$) for all Case 1 panel systems was between 0.64 and 0.86, and the maximum allowable indoor humidity ($\text{RH}_{\text{max}}$) to prevent internal surface condensation was between 48% and 75%. The $f_{\text{Rsi,min}}$ values of Case 1 did not reach a serious risk level. However, $f_{\text{Rsi,min}}$ and $\text{RH}_{\text{max}}$ of Case 2 were 0.97 and 94%, this means the thermal bridges significantly increased the internal surface condensation risk.

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