

Evaluation of alternatives for reducing thermal bridges in metal panel curtain wall systems



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ABSTRACT

Building envelopes incorporate thermal bridges, through which heat is transferred in either two or three dimensions. These thermal bridges lead to undesirable heat transfer, thereby resulting in an overall reduction in the insulation performance. In this study, alternatives were proposed to reduce the linear and point thermal bridges found in steel truss metal panel curtain wall systems in which metal panels fabricated by covering six faces of insulation with metal are fixed to the truss. Three-dimensional heat transfer simulations and mock-up tests were conducted to evaluate the insulation performance of the alternatives. Also, life-cycle costs were analyzed to evaluate the economic feasibility of the selected alternative. The evaluation results showed that the alternative 2, in which the lengths of the aluminum molding at the sides of the metal panel were reduced and for which thermally broken brackets were used, was the most effective alternative. The mock-up test performed in winter showed that the alternative 2 largely reduced the heat loss through the thermal bridges and had better insulation performance. Assuming a lifetime of 40 years, the alternative 2 would reduce the life cycle costs by 10.9% relative to the existing case.

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1. Introduction

In response to the threat of climate change caused by increased emissions of greenhouse gases, policies have been enforced around the world to reduce these emissions. In the building sector, mandatory green building policies have been implemented in the shape of new or revised energy-related building regulations. For example, the European Union (EU) has proposed a “zero energy goal” to be implemented for all new buildings by 2020. The UK is aiming to attain zero carbon emissions for new buildings by 2016. Germany is aiming to attain passive house level performance for all new buildings by 2015. The Korean Government has also set a national greenhouse gas reduction goal for the building sector of 26.9% of the business-as-usual (BAU) level to be attained by 2020. To achieve this goal, the Korean Government is promoting a policy aimed at achieving a reduction in annual energy consumption in non-residential and residential buildings of 30% and 60%, respectively, by 2017 and zero energy consumption for all new buildings by 2025 [1].

In 2010, the energy consumed by buildings accounted for 21.2% of the total energy consumption of Korea, with this being an increasing trend. According to the 2011 National Energy Consumption Survey, relative to 2007, the energy consumption of non-residential and residential buildings had increased by 5.2% and 5.1%, respectively. This increase was assumed to be due to an increase in heating and cooling energy consumption caused by unusual temperatures and increases in the number of large buildings with high energy consumptions. In addition, the heating and cooling energy consumption of non-residential buildings accounted for 60% of their total energy consumption, while the heating energy consumption of residential buildings accounted for 75% of their total [2]. These survey results indicate that reducing the heating and cooling energy consumption is very important to decreasing the overall energy consumption of buildings.

Considering that the building envelope is the main path through which heat is lost or gained in buildings, its insulation performance is very important to the heating and cooling energy consumption. Thus, the insulation performance of the building envelope needs to be improved in order to attain the energy saving and greenhouse gas reduction goal for buildings. For this reason, the Korean Government has announced a detailed step-by-step plan to increase the insulation performance required by building envelopes, with

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Nomenclature

A	Surface area of VIP perpendicular to the heat flow direction (m^2)
A_e	External area (m^2)
A_{wall}	Area of external non-vision wall (m^2)
$\text{COP}_{\text{EHP}_c}$	Coefficient of performance of electric heat pump in cooling mode
$\text{COP}_{\text{EHP}_h}$	Coefficient of performance of electric heat pump in heating mode
Cost_{con}	Construction cost (Won/m^2)
Cost_{en}	Annual energy cost (Won/m^2)
D	Material roughness coefficients, (8.23, corresponding to “Very smooth” surface)
d	Thickness of VIP in heat flow direction (m)
E	Material roughness coefficients, (3.33, corresponding to “Very smooth” surface)
E_c	Cooling energy use (MJ/m^2)
E_h	Heating energy use (MJ/m^2)
E_m	Energy use of m-month (MJ/m^2)
E_t	Total solar radiation incident on surface (W/m^2)
F	Material roughness coefficients, (−0.036, corresponding to “Very smooth” surface)
$f_{\text{Rsi}_{\text{min}}}$	Lowest temperature factor
h_o	Outdoor surface heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$)
i	Inflation rate (%)
n	Lifetime (years)
n_c	Number of measuring points at center of metal panel
n_{TBk}	Number of measuring points at thermal bridge
PW	Present worth coefficient
p	Perimeter of VIP surface (m)
Q_c	Heat gain during cooling period (MJ/m^2)
Q_h	Heat loss during heating period (MJ/m^2)
q_{tot}	Total heat loss (W) Total heat loss (W)
R	Interest rate (%)
Rate_m	Electricity rates of m-month according to season and time-period (Won/kWh)
ΔR	Difference between long-wave radiation incident on surface from sky and surroundings and radiation emitted by blackbody at outdoor air temperature (W/m^2)
T_c	Surface temperature at center of metal panel ($^{\circ}\text{C}$)
T_i	Indoor air temperature ($^{\circ}\text{C}$)
T_o	Outdoor air temperature ($^{\circ}\text{C}$)
$T_{\text{si}_{\text{min}}}$	Lowest indoor surface temperature ($^{\circ}\text{C}$)
T_{sol}	Sol-air temperature ($^{\circ}\text{C}$)
T_{TBk}	Surface temperature at thermal bridge ($^{\circ}\text{C}$)
$\bar{T}_c$	Average surface temperature at center of metal panel ($^{\circ}\text{C}$)
$\bar{T}_{\text{TBk}}$	Average surface temperature at thermal bridge ($^{\circ}\text{C}$)
$\Delta \bar{T}_{c-\text{TBk}}$	Average surface temperature difference between center and thermal bridge ($^{\circ}\text{C}$)
U_{1-D}	Thermal transmittance assuming one-dimensional heat transfer ($\text{W}/\text{m}^2\text{K}$)
U_{eff}	Effective thermal transmittance ($\text{W}/\text{m}^2\text{K}$)
v	Wind speed (m/s)
α	Solar radiation absorptance of surface
ε	Hemispherical emittance of surface
λ_{cop}	Center-of-panel thermal conductivity (W/mK)
λ_{eff}	Effective thermal conductivity (W/mK)
ψ_{VIP}	Linear thermal transmittance (W/mK)

stricter requirements being introduced in 2015, 2017, and 2019 [3].

The type of building envelope varies depending on the purpose and design of a building. Depending on the construction methods and the components used, different thermal bridges can occur in the envelope, through which heat is transferred in either two or three dimensions. Thermal bridges allow undesirable heat transfer, and thus are a main cause of the overall reduction in the insulation performance of a building envelope. A large number of studies have examined the reduction in the insulation performance of a building envelope due to thermal bridges. Several studies have compared heat losses through linear thermal bridges when internal and external insulation was applied to concrete external walls [4–6]. Other studies have examined heat loss through point thermal bridges when exterior materials, such as metal and stone, and insulation materials are fixed to a concrete external wall using fasteners [7,8]. In the case of curtain walls, more thermal bridges arise because of the construction method, in which components are assembled either on-site or in the factory. A number of studies have examined thermal bridges in aluminum curtain walls [9] and stone curtain walls [10], and they evaluated the reduction in the insulation performance and proposed methods for improving the insulation performance. There have also been studies of the thermal bridges in other types of external walls such as lightweight walls [11–13] based on steel frames, precast concrete sandwich walls [14], double brick walls [15], and general sandwich panels [16]. In addition, studies of insulation performance evaluation methods that consider the thermal bridges in steel frame wall systems, built-up wall systems, and concrete walls have also been conducted [17–21].

Recently, curtain walls have become popular as the envelope of high-rise buildings. For curtain walls, metals with a low thermal resistance are used for the main components which are assembled into units. They have various shapes and sizes. In particular, metal fixing components such as trusses, brackets, and bolts penetrate the insulation layer in non-vision parts for fixing the insulation to the structure. These components become point thermal bridges that increase the heat transfer. In many countries, including Korea, the non-vision parts of curtain walls are required to meet a required U-factor (thermal transmittance) of walls, as specified in the building codes [22–24]. However, in many U-factor assessments, thermal bridges are not taken into consideration so the actual insulation performance will be much poorer than the assessment results, even if the required U-factor is satisfied. In particular, considering that the ratio of the heat loss through thermal bridges relative to the overall heat loss will be larger as the overall insulation performance of the envelope is enhanced [25,26], curtain walls for reducing thermal bridges are needed to deal with the enhanced insulation performance design criteria to be applied in the future.

Therefore, this study proposed alternatives for reducing thermal bridges in steel truss metal panel curtain walls in which metal panels fabricated by covering six faces of insulation with metal are fixed to the truss, and their thermal performance and economic feasibility were evaluated. In the alternatives, the U-factor at the center of the metal panel is very low in order to be able to conform to future enhanced insulation performance design criteria. At first, the linear and point thermal bridges of an existing case were defined and three alternatives with different details at the thermal bridges were proposed. The insulation performance of these alternatives was evaluated through three-dimensional steady-state heat transfer simulations to select the most effective alternative. In addition, a mock-up test was conducted during the winter with the existing case and the selected alternative, to verify the enhanced insulation performance of the selected alternative. Furthermore, the construction costs of the selected alternative were calculated. The annual energy costs were calculated through three-dimensional unsteady-

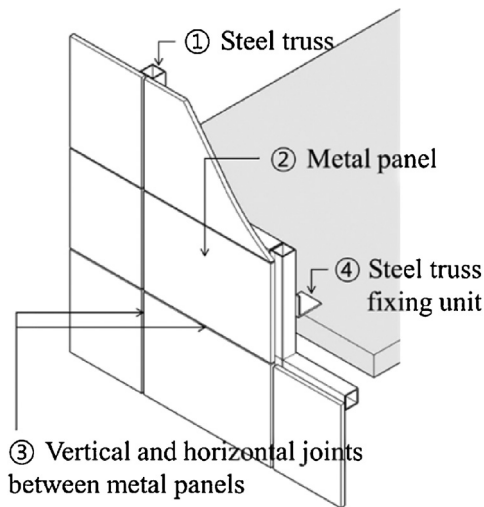


Fig. 1. Construction of steel truss metal panel curtain wall system.

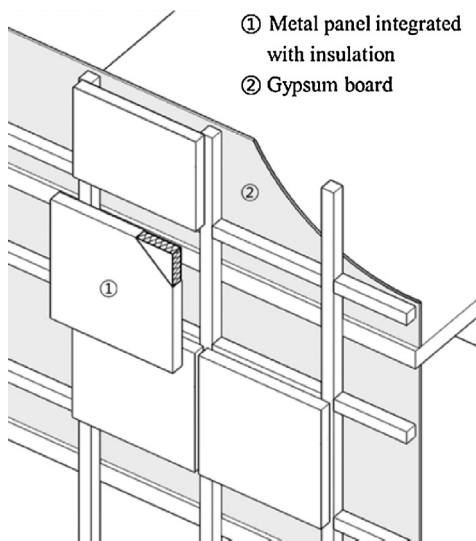


Fig. 2. Components of steel truss metal panel curtain wall system.

state heat transfer simulations. Then, their life cycle costs (LCCs) were compared to assess their economic feasibility.

2. Alternatives for reducing thermal bridges in steel truss metal panel curtain wall systems

2.1. Thermal bridges in existing systems

Classifications and construction methods of steel truss metal curtain wall systems were reported in the previous study [27]. A metal panel type steel truss curtain wall system is conventionally built as follows. As shown in Fig. 1, a cross or vertical steel truss (1) is installed on the structure first. Then, a metal panel (2) is fixed to the steel truss. Finally, the vertical and horizontal joints (3) between the metal panels are filled with back-up materials and then finished with sealant. The use of steel trusses as structural members is less expensive than applying aluminum mullions and transoms, such that the construction method is widely adopted for general buildings.

As shown in Fig. 2, a steel truss metal panel curtain wall system consists of metal panels (1) and an interior material (2, normally, gypsum board is applied). Metal panels are manufactured in factories by wrapping insulation with steel or aluminum sheet. They

are fixed to the steel trusses using H-shaped brackets or screws, as shown in Fig. 3. In general, a bracket-based fixing method, which makes construction more convenient, is widely adopted. When the horizontal length of a metal panel is less than 2 m, it is possible to fix the metal panel at two points, specifically, the right- and left-hand ends at the top and bottom of the metal panel, so that only vertical trusses are needed to support the metal panels. On the other hand, when the horizontal length of a metal panel unit exceeds 2 m, the metal panel is generally fixed at more than three points including the right- and left-hand ends and the midpoint of the top and bottom edges of the panel, so that both vertical and horizontal trusses are needed. For steel truss metal panel curtain wall systems, the main linear thermal bridges occur at the vertical and horizontal joints between the metal panels, where the insulation is non-continuous. In addition, a variety of metal fasteners such as brackets and screws, which have a high thermal conductivity, are point thermal bridges which can be connected to a linear thermal bridge. Fig. 4 shows infrared thermal images of a multi-use building in winter that was built using the steel truss metal panel curtain wall system. It can clearly be seen that there is considerable heat loss through the vertical and horizontal joints between the metal panels.

2.2. Setup of existing case and proposal of alternatives for reducing thermal bridges

2.2.1. Existing case

A section of the existing case is shown in Fig. 5(a). It includes the main thermal bridges at the joints between the metal panels and the bracket. The existing case is that of an actual product used in a steel truss metal panel curtain wall system. In the existing case, a bracket-based fixing method, which is widely applied due to its convenient construction, is used to fix the metal panel. To make the metal panel slim and light-weight for convenient application to the construction of high-rise buildings, as well as being able to comply with future enhanced insulation performance design criteria, vacuum insulation panels (VIPs) are used as insulation in the metal panel. In addition, to protect the VIPs, which are vulnerable to local damage from sharp objects, and to alleviate linear thermal bridges at the joints between the VIPs themselves, the insulation consists of two layers, namely, phenolic foam and the VIP. In the existing case, the front and rear surfaces of a metal panel are made of steel sheet, and the upper, lower, right, and left edges of the metal panel are formed of aluminum moldings in which there is a groove for inserting the bracket. In addition, a polyurethane thermal breaker is incorporated into the aluminum molding as shown in Fig. 6(a). The existing case uses an aluminum bracket, as shown in Fig. 7(a).

2.2.2. Alternatives for reducing thermal bridges

Sections of the alternatives are shown in Fig. 5(b)–(d). Alt 1 reduces the length of the existing aluminum molding by as much as 1/3 of the metal panel thickness, which corresponds to the minimum length required to insert a bracket, in order to reduce linear thermal bridges resulting from the aluminum moldings at the joints between metal panels, as shown in Fig. 6(b). The remaining 2/3 of the metal panel thickness was fitted with a PVC-foam pad to ensure air-tightness between the metal panels and to prevent the insulation in the metal panel from being exposed. In the case of Alt 2, a thermally broken bracket replaces the aluminum bracket of Alt 1. The thermally broken bracket is the same as the aluminum bracket except that a polyurethane thermal breaker is inserted into the bracket body, as shown in Fig. 7(b) in order to reduce the effect of the point thermal bridge caused by the brackets. In the case of Alt 3, its aluminum molding is similar to that of Alt 2 except that a polyurethane thermal breaker is inserted into the molding to further reduce the heat loss, as shown in Fig. 6(c).

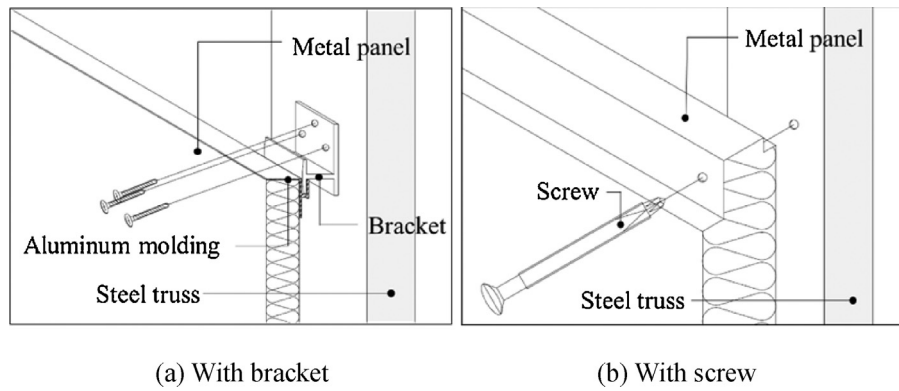


Fig. 3. Fastening of metal panel to steel truss.

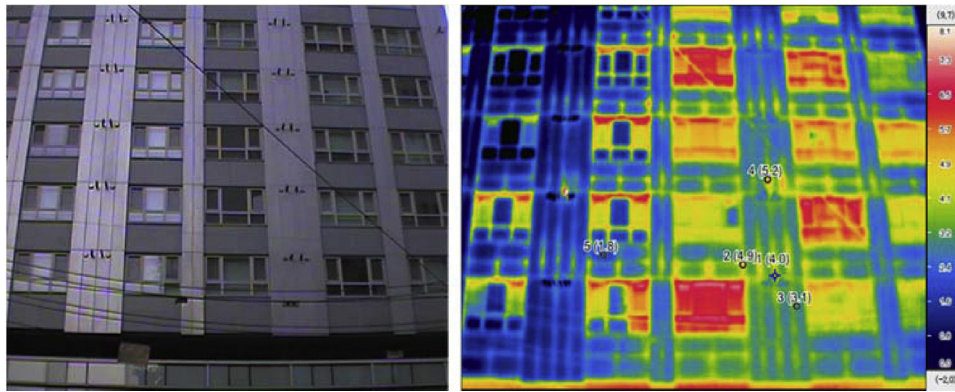


Fig. 4. Infrared thermal image of steel truss metal panel curtain wall system in winter.

The thermally broken bracket addressed by this study was designed to support a metal panel measuring 2000 mm (width) by 1000 mm (height) and weighing 28 kg. Using Midas Gen [28], a structural analysis program, the structural performance of the thermally broken bracket was investigated. The results [29] showed that the same structural performance as existing aluminum brackets could be obtained under a wind load of 100.0 kgf/m², which is the design wind load for a 20-m high external wall in Seoul, as provided by KBC [30].

3. Evaluation of insulation performance through steady-state heat transfer simulation

Using Physibel TRISCO v.12.0w, the insulation performance of the existing case and alternatives were evaluated. TRISCO is a three-dimensional steady-state heat transfer simulation program, which can solve the heat balance equation by applying the finite difference method, such that high-precision calculations for the complex elements of buildings are possible [31]. Using the heat loss and lowest indoor surface temperature obtained through heat transfer simulations, Eqs. (1) and (2) are used to calculate the effective U-factor and lowest temperature factor, thereby enabling the evaluation of the insulation performance and surface condensation risk. The temperature factor is defined as the ratio of the difference between the indoor surface temperature and outdoor temperature to the indoor to outdoor temperature difference. The closer this value is to 1, the less likely it is that condensation will occur [32].

$$U_{eff} = \frac{q_{tot}}{A_e \times (T_i - T_o)} \quad (1)$$

$$f_{Rsi_min} = \frac{T_{si_min} - T_o}{T_i - T_o} \quad (2)$$

3.1. Overview of simulation

3.1.1. Simulation model

The insulation performance was evaluated for a typical external wall area including all possible thermal bridges. A typical external wall area was determined as shown in Fig. 8 according to the modeling principle for the detailed calculation of heat flow through thermal bridges as provided in ISO 10211 [33], assuming that the area is part of a non-vision external wall in a virtual office building and that the wall consists of metal panels measuring 2000 mm (width) by 1000 mm (height). In ISO 10211, for non-repeated thermal bridges such as wall to wall and wall to roof junctions, the cutting plane of the flanking element was placed at the larger of 1 m and three times the thickness of the flanking element from the thermal bridge element. For repeated thermal bridges such as the joists of a brick wall and wood or metal studs, the middle point between them was set as the cutting plane.

A simulation model based on the above method is shown in Fig. 9. The model has an external surface measuring 2012 mm (width) by 3036 mm (height). To make a comparison between the existing case and the alternatives, the areas of the internal and external surfaces were the same in every case. Some elements that do not significantly affect the insulation performance, such as the I-beam at the bottom of the slab and the fasteners of a ceiling panel, were not included in the simulation model. The insulation thickness of the simulation model was 60 mm, consisting of 40 mm of phenolic foam and 20 mm of VIP. The U-factor at the center of the metal panel, not including any thermal bridges, was 0.125 W/m²K, and the total U-factor (U_{1-D}) of the external wall including the interior gypsum board was 0.122 W/m²K.

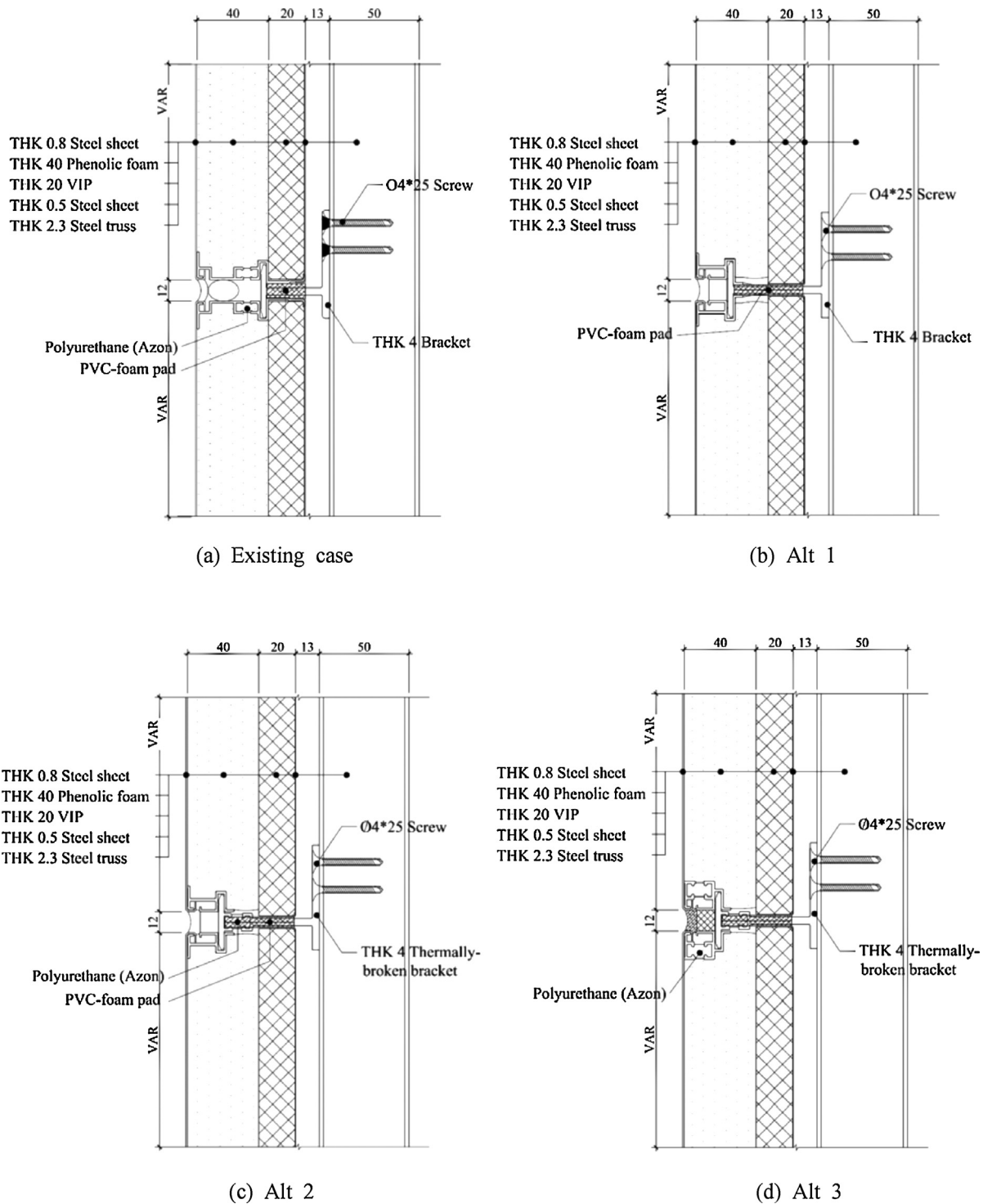


Fig. 5. Details of joints between panels and bracket.

Table 1
Boundary conditions for steady-state heat transfer simulations.

	Air temperature (°C)	Surface heat transfer coefficient (W/m ² K)
Outdoor	−11.3	23.25
Indoor	20.0	9.09

3.1.2. Boundary conditions and physical properties

Tables 1 and 2 list the boundary conditions and material properties applied to the simulation. The outdoor temperature was set to

the heating design outdoor temperature in Seoul, −11.3 °C, while the indoor temperature was set to the office heating set-point temperature, 20.0 °C, as provided in the Korean Code for Energy-Efficient Building Design [22]. The outdoor and indoor surface heat transfer coefficients were 23.25 and 9.09 W/m²K, respectively, provided in the same Code. For the convenience of modeling, the VIP was modeled with the effective thermal conductivity. In other words, the VIP core and envelope were not modeled separately. Using the effective thermal conductivity, the model included the thermal bridging effect due to the metalized film barrier envelop-

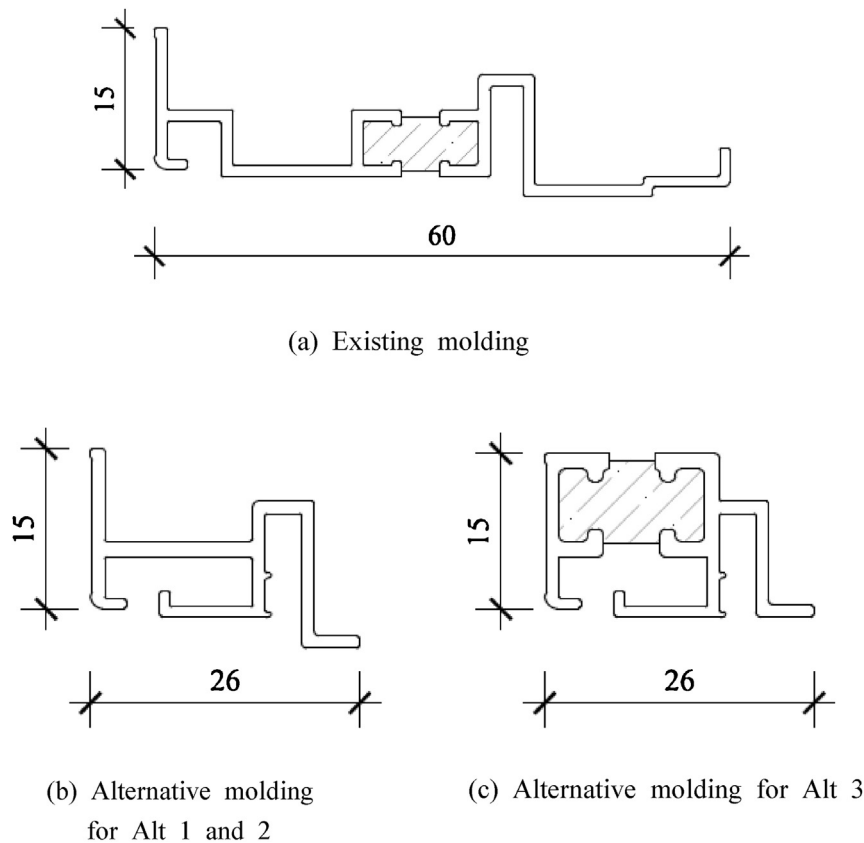


Fig. 6. Existing aluminum molding and alternatives for Alt 1, 2, and 3.

Table 2
Material properties.

	Thermal conductivity (W/mK)	Density (kg/m ³)	Specific heat (J/kgK)
Concrete	1.6	2240	879
Gypsum board	0.180	940	1173
Steel	45.3	7830	500
Aluminum	221.0	2740	896
Cavity air	–	1.184	1007
Glass wool	0.034	52	657
Polyurethane foam	0.050	70	1500
Silicon sealant	0.350	1200	1000
Paint	0.19	891	4050
Linoleum	0.170	1200	1400
VIP ^a	0.00424	192	850
Phenolic foam	0.019	65	1500
Polyurethane thermal breaker (Azon)	0.120 ^b	1191 ^b	1347 ^d
PVC foam pad	0.0389 ^c	96.1 ^c	1434 ^d

^a IEA/ECBCS Annex 39 (2005).

^b Test reports from Korea Testing and Research Institute (2014).

^c Specification of manufacturer (2002).

^d Test reports from NICEM of Seoul National University (2014).

ing the VIP core. The effective thermal conductivity was obtained using Eq. (3) [34]. In Eq. (3), the linear thermal transmittance (ψ_{VIP}) value of 9.19×10^{-3} W/mK for a metalized barrier with 300 nm of aluminum and small seams folded at the panel edges was obtained from [34], which describes a case that closely matches the envelope of the ENERVAC (VIP product applied in this study, manufactured by OCI Ltd., Seoul, Korea). The center-of-panel thermal conductivity 0.0035 W/mK for VIP (λ_{cop}) was given by the ENERVAC manufacturer. The size of the VIP unit applied in Eq. (3) is 1000 mm (width) by 1000 mm (height). No significant problem is assumed to exist in

the VIP modeling method using the effective thermal conductivity because the aim of this study is to compare alternatives under the same conditions. In addition, this modeling method was applied in other studies. Park et al. [35] evaluated various external insulation systems using VIPs with three-dimensional heat transfer simulations, in which the VIPs were modeled with their effective thermal conductivity. Sallee et al. [36] evaluated the various thermal breaking systems using VIPs with two-dimensional heat transfer simulations, in which the VIPs were modeled with a single thermal conductivity. They [36] reported that the comparison of the simulation and experimental profiles along the external wall showed a good correlation. However, it is necessary to model the VIP core and envelope separately for cases that focus on the heat transfer through the VIP envelope. For the cavity between the metal panel and the gypsum board, an equivalent thermal conductivity was used, which satisfies the thermal resistance of the cavities provided in the Korean Code for Energy-Efficient Building Design. For other cavities in the simulation model, the equivalent thermal conductivity, calculated automatically according to the shape and heat transfer direction, was applied.

$$\lambda_{eff} = \lambda_{cop} + \psi_{VIP} \times d \times p/A \quad (3)$$

3.2. Results of simulation

3.2.1. Analysis of effective U-factor

Table 3 and Fig. 10 show the simulation results for the existing case and Alts 1–3. The heat losses of the cases can be ranked as follows: existing case > Alt 1 > Alt 2 > Alt 3. The heat loss of the existing case was 100.2 W, which is the largest because the additional heat loss through the aluminum moldings was considerable, as shown in Fig. 10(a). Also, the effective U-factor was 0.524 W/m²K, which

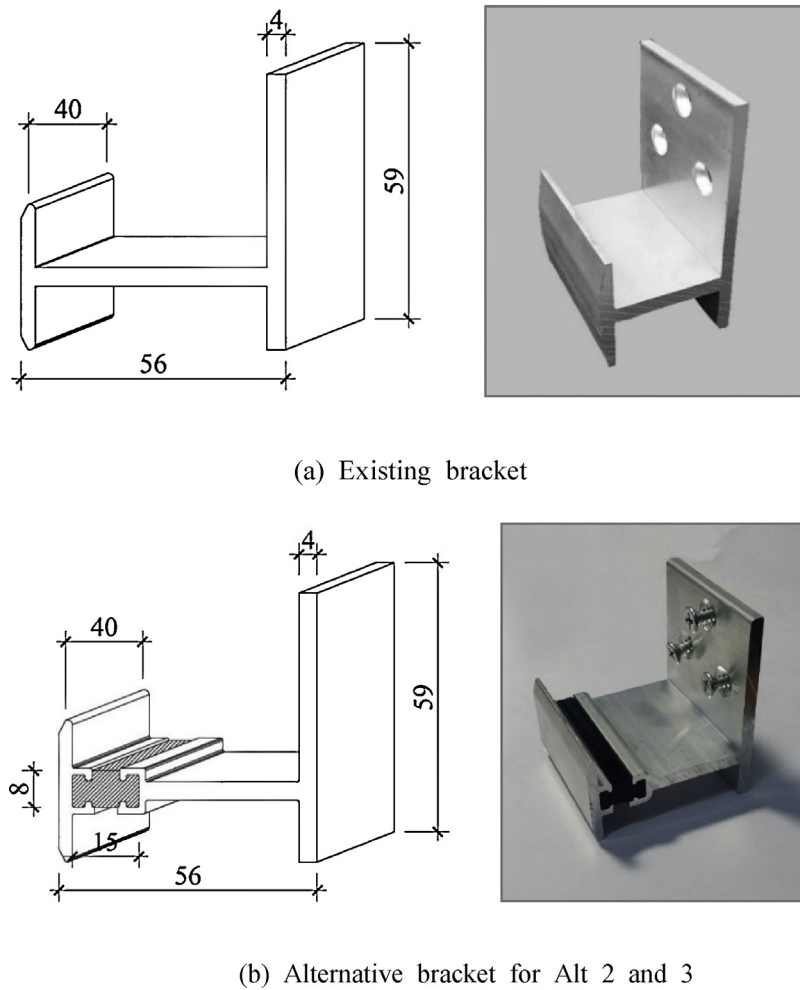


Fig. 7. Existing aluminum bracket and alternative for Alt 2 and 3.

Table 3
Simulation results.

	Existing case	Alt 1	Alt 2	Alt 3
U_{1-D}	0.122 W/m ² K			
Heat loss	100.2 W	55.2 W	32.1 W	31.9 W
Rate of increase and decrease relative to existing case	–	–44.9%	–68.0%	–68.2%
U_{eff}	0.524 W/m ² K	0.289 W/m ² K	0.168 W/m ² K	0.167 W/m ² K
Lowest indoor surface temperature	17.2 °C	17.4 °C	19.3 °C	19.2 °C
Lowest temperature factor	0.91	0.92	0.98	0.97

was 4.3 times higher than U_{1-D} . The heat loss of Alt 1 was 55.2 W, which was a reduction of 44.9% relative to the existing case while the effective U-factor was 0.289 W/m²K. However, the heat loss through the existing aluminum bracket was still significant, while the heat loss through the aluminum molding was greatly reduced, as shown in Fig. 10(b). The heat loss of Alt 2 was 32.1 W, which was reduced by 68.0% relative to the existing case, while the effective U-factor was 0.168 W/m²K. The heat loss of Alt 2 was reduced by 41.8% compared to Alt 1, although the two cases used the same molding. This result showed that the reduction in the heat loss by applying the thermally broken bracket was also considerable. The heat loss of Alt 3 was 31.9 W and its effective U-factor was 0.167 W/m²K, which was nearly the same as that of Alt 2. Alt 3, in which a polyurethane thermal breaker was inserted into the aluminum molding of Alt 2, offered no significant advantage over Alt 2 in terms of cost effectiveness. Thus, Alt 2 can be selected as being the most effective.

3.2.2. Analysis of indoor surface condensation risk

In all cases, the lowest indoor surface temperature was found at the lower part of the interior gypsum board in the upper floors. The lowest indoor surface temperature was found to be 17.2 °C for the existing case, 17.4 °C for Alt 1, 19.3 °C for Alt 2, and 19.2 °C for Alt 3. For Alt 1, despite the heat loss being reduced by 44.9% relative to that of the existing case, the lowest indoor surface temperature was similar to that of the existing case. This was due to the reduction in the local surface temperature caused by the existing bracket. In the case of Alt 2 and Alt 3, the lowest indoor surface temperature was 2.0–2.1 °C higher than that of the existing case. The lowest temperature factor was found to be within a range of 0.91–0.98 in all cases. Given that the recommended lowest temperature factor for new office buildings in the UK [37] and the Netherlands [38] is 0.50 and the recommended lowest temperature factor for all buildings in Germany [39] is 0.7, the surface condensation risk was expected to be very low in all cases.

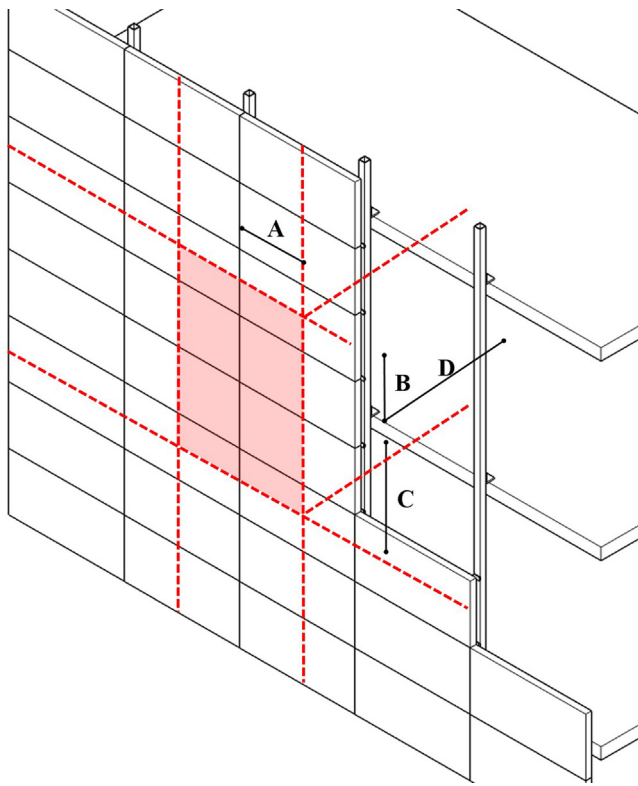


Fig. 8. Cut-off plane for evaluation; (A) from vertical truss to horizontal midpoint of panel (B) from a slab to the vertical midpoint of panel (more than 1.0 m) (C) from slab to vertical midpoint of panel, including ceiling plenum space (greater than height of plenum space + 1.0 m) (D) from inside surface to cutting plane (greater than 1.0 m).

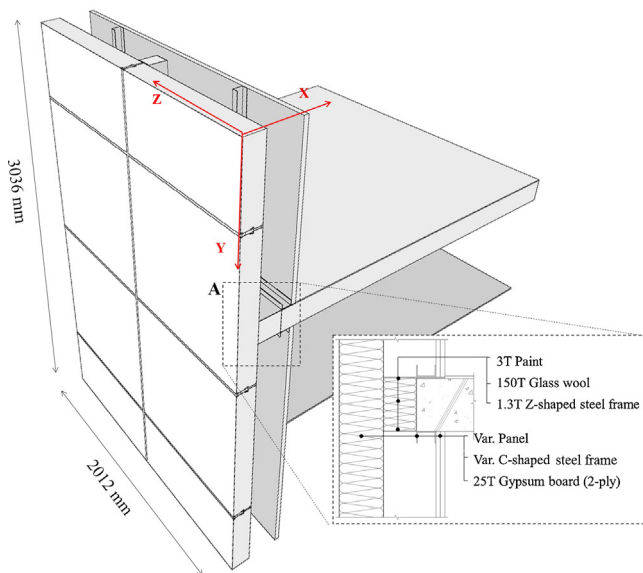


Fig. 9. Simulated region.

4. Evaluation of insulation performance through mock-up test performed in winter

In the evaluation of the insulation performance based on the heat transfer simulation, it is difficult to take all the complex heat transfer characteristics between the wall and adjacent indoor and outdoor environments into consideration [10]. Thus, the improvements in the insulation performance of Alt 2, which was selected as the most effective alternative in the previous section, were eval-

Table 4
Specifications of measuring equipment.

Type (Model)	Specification
Infrared thermal camera (TH7800)	- Measurement range: -30 to 250°C - Temperature resolution: 0.05 and 0.1°C
Thermocouple (TS-T25-TE)	- Measurement range: -200 to 350°C - Accuracy: $\pm 0.5^{\circ}\text{C}$ or 0.4%
Self-adhesive thermocouple (Omega, SA1XL-T)	- Measurement range: -270 to 400°C - Accuracy: $\pm 0.5^{\circ}\text{C}$ or 0.4% at 0–350°C
Data logger (GL820)	- Clock accuracy: $\pm 0.002\%$ (ambient temperature 23°C) - Accuracy: $\pm (0.1\% \text{ of reading} + 1.5^{\circ}\text{C})$ at -200 to -100°C and $\pm (0.1\% \text{ of reading} + 0.5^{\circ}\text{C})$ at -100 to 400°C
Air temperature logger (TR-74Ui)	Accuracy: $\pm 0.5^{\circ}\text{C}$
Global solar radiation pyranometer (LP PYRA 03)	- Measurement range: 0–2000 W/m^2 at -40 to 80°C - Accuracy: Class 2 pyranometer as defined in ISO 9060

uated by conducting a mock-up test in winter. Test specimens of the existing case and Alt 2 were manufactured and installed in the same way as they would be in an actual application. To analyze the insulation performance of the existing case and Alt 2, infrared thermal images of the external surfaces were captured and the internal and external surface temperatures and the cavity temperature were measured during the mock-up test.

4.1. Overview of mock-up test

The test was conducted from Jan 29 to Feb 9, 2015. The test facility is shown in Fig. 11om. The walls of the test rooms consisted of 100-mm urethane boards. An opening, measuring 1810 mm (width) by 3520 mm (height), into which the specimens could be inserted, was provided in the south-facing side of the test room. The indoor temperatures in both the test rooms and control room were controlled by an electric heat pump (EHP). The temperatures in the test and control rooms during the mock-up test were set to 25°C to minimize the heat loss through walls other than the specimen.

The specimen consisted of a metal panel, vertical steel truss, cavity, and gypsum board. The metal panel used for the steady-state heat transfer simulation measured 2000 mm (width) by 1000 mm (height). However, in the mock-up test, considering the size of the opening for installing the specimen, six 900 mm $\times$ 900 mm metal panels, formed by cutting an 1800 mm $\times$ 900 mm metal panel horizontally, were installed as shown in Fig. 13 and its floor plan and horizontal and vertical sections are shown in Fig. 12. The test facility consisted of three test rooms and a control room. Urethane boards were additionally installed in the gap (A in Fig. 13) between the right- and left-hand sides of the specimen and the opening of the test room, as well as in the gap (B in Fig. 13) between the top of the specimen and the opening to minimize the heat loss. Fig. 14 shows the process for installing the specimen. Infrared thermal images of the external surfaces of the specimen were captured, and the internal and external surface temperatures, cavity temperatures, indoor and outdoor air temperatures, global solar radiation incident on the vertical surface, and outdoor wind speed were measured every five minutes. The measurement equipment is shown in Fig. 15, and the locations at which the temperatures were measured are shown in Fig. 16. Table 4 lists the specifications and accura-

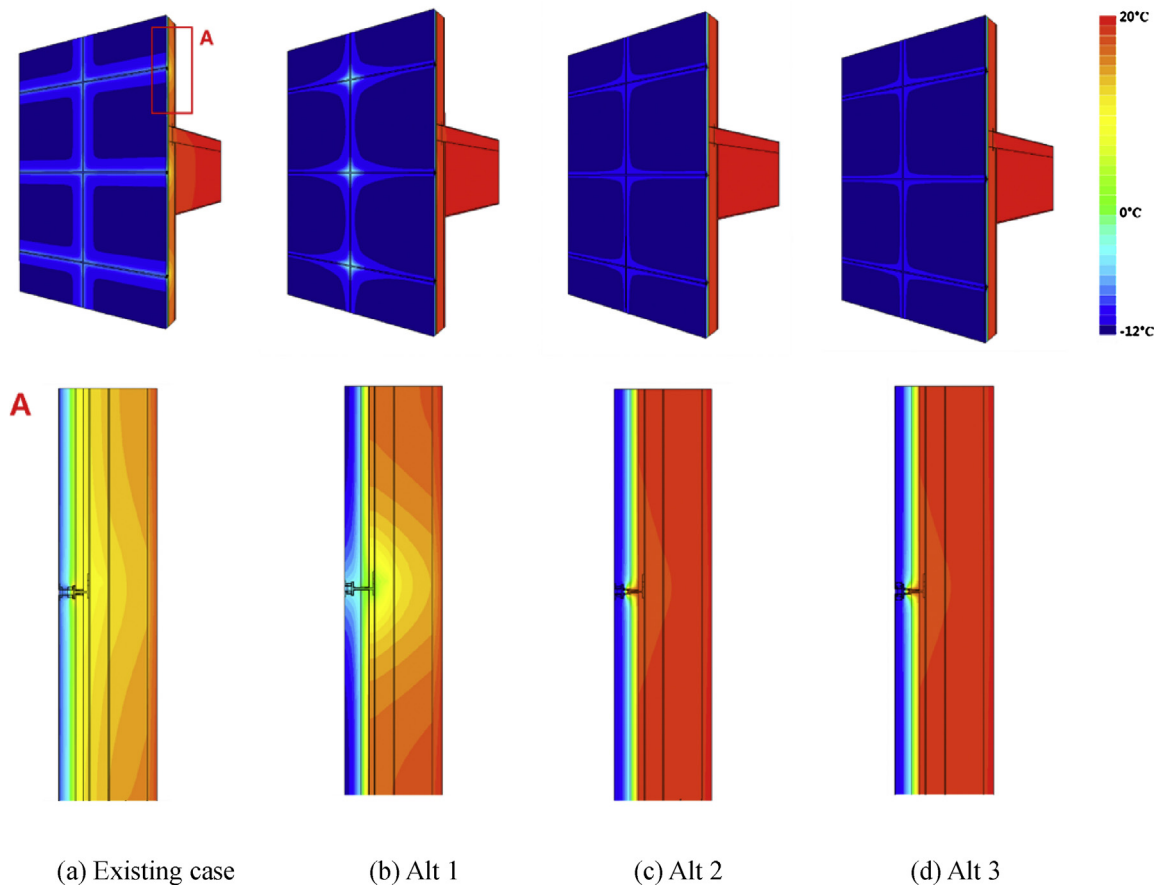


Fig. 10. Temperature distributions across external surfaces and vertical sections at joints between metal panels.



Fig. 11. Test facility.

cies of the measurement equipment. To reduce the measurement errors, all the sensors and data loggers were calibrated beforehand. The two specimens of the existing case and Alt 2 were carefully installed so that they were tested under the same boundary conditions as closely as possible. The thermocouples were also carefully installed at as close to the same locations of the two specimens as possible. The temperatures of the two test rooms for the existing case and Alt 2, controlled by EHPs, were maintained at an average

of approximately 25 °C during the mock-up test. The temperature distributions of the two test rooms are shown in Fig. 21 and Table 6.

4.2. Results of mock-up test

4.2.1. Analysis of infrared thermal images

In winter, the external surface temperature of the thermal bridge areas is higher than that of the non-thermal bridge areas due to the additional heat loss, whereas the internal surface tem-

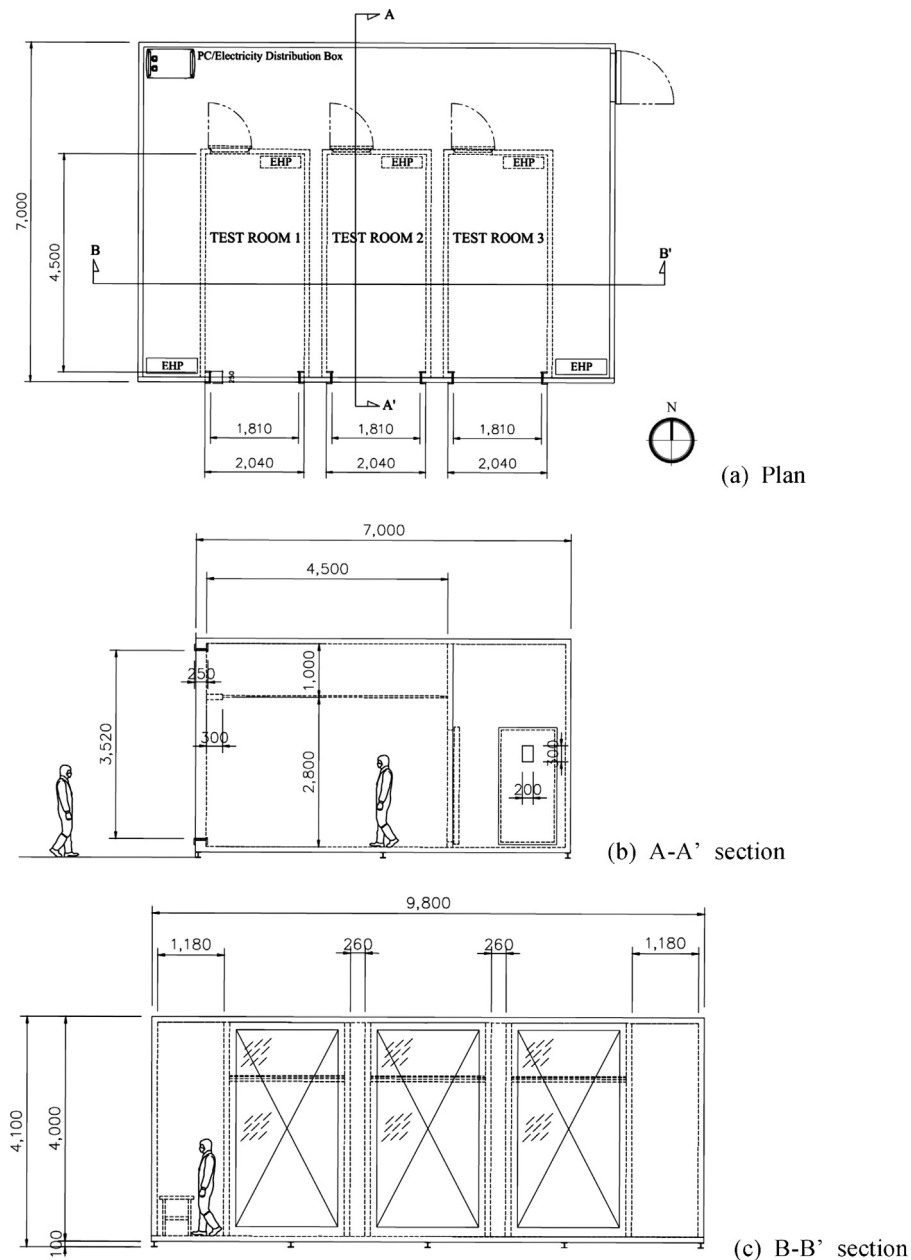


Fig. 12. Plan and section of test facility.

perature is lower than that of the non-thermal bridge areas. The difference in the surface temperature between the thermal bridge and non-thermal bridge areas increases as the heat loss through the thermal bridge increases. Infrared thermal images of the external surface of the existing case and Alt 2 are shown in Fig. 17. The infrared thermal images were captured at 05:00 on Feb 9 (before sunrise), while the outdoor air temperature was -15.1°C and the humidity was 67%. When the thermal images were captured, the emissivity of the external surface was set to 0.66 for the sheet steel, obtained from [40].

The external surface temperatures at the center of each metal panel, which is a non-thermal bridge area for both the existing case and Alt 2, were similar to the outdoor temperature or lower than the outdoor temperature due to the night sky radiation. This means that the heat loss through the center of the metal panels was very small. For the existing case, the linear heat loss through the vertical and horizontal joints between the metal panels was clearly revealed. In addition, the point heat loss at the cross joints between the metal

panels, where the aluminum brackets were installed, was found to be very large. On the other hand, the heat loss through the vertical and horizontal joints, as well as through the cross joints between the metal panels were significantly reduced in the case of Alt 2.

The distribution of the external surface temperature at A-A' and B-B' is shown in Figs. 18(a) and (b), respectively. The external surface temperature of the vertical joint between the metal panels of the existing case was -14.4°C , which was 5.0°C higher than that at the center of the metal panel (see ① in Fig. 18(a)). The external surface temperature of the cross joint between the metal panels of the existing case was -13.0°C , which was 7.0°C higher than that at the center of the metal panel (see ① in Fig. 18(b)). On the other hand, the external surface temperature of the vertical joint between the metal panels of Alt 2 was -17.4°C , which was 2.6°C higher than that at the center of the metal panel (refer to ② in Fig. 18(a)), while the external surface temperature of the cross joint between the metal panels was -17.1°C , which was 2.9°C higher than that at the center of the metal panel (see ② in Fig. 18(b)). For Alt 2, the

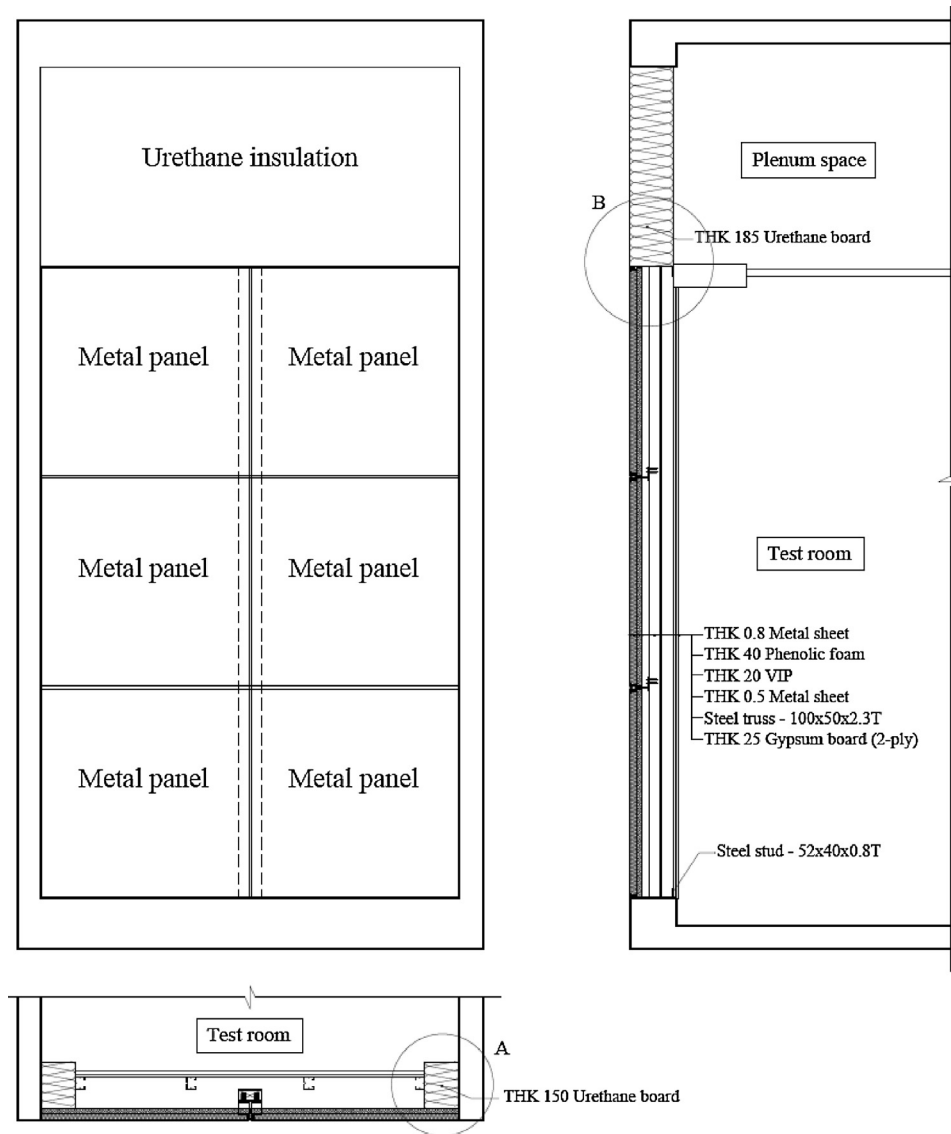


Fig. 13. Specimens.



Fig. 14. Installation of specimen: (a) Urethane boards, (b) Vertical truss for fixing metal panels and steel frame for fixing gypsum boards, (c) Gypsum boards, (d) Metal panels and urethane boards, and (e) Joint sealing and sensors.

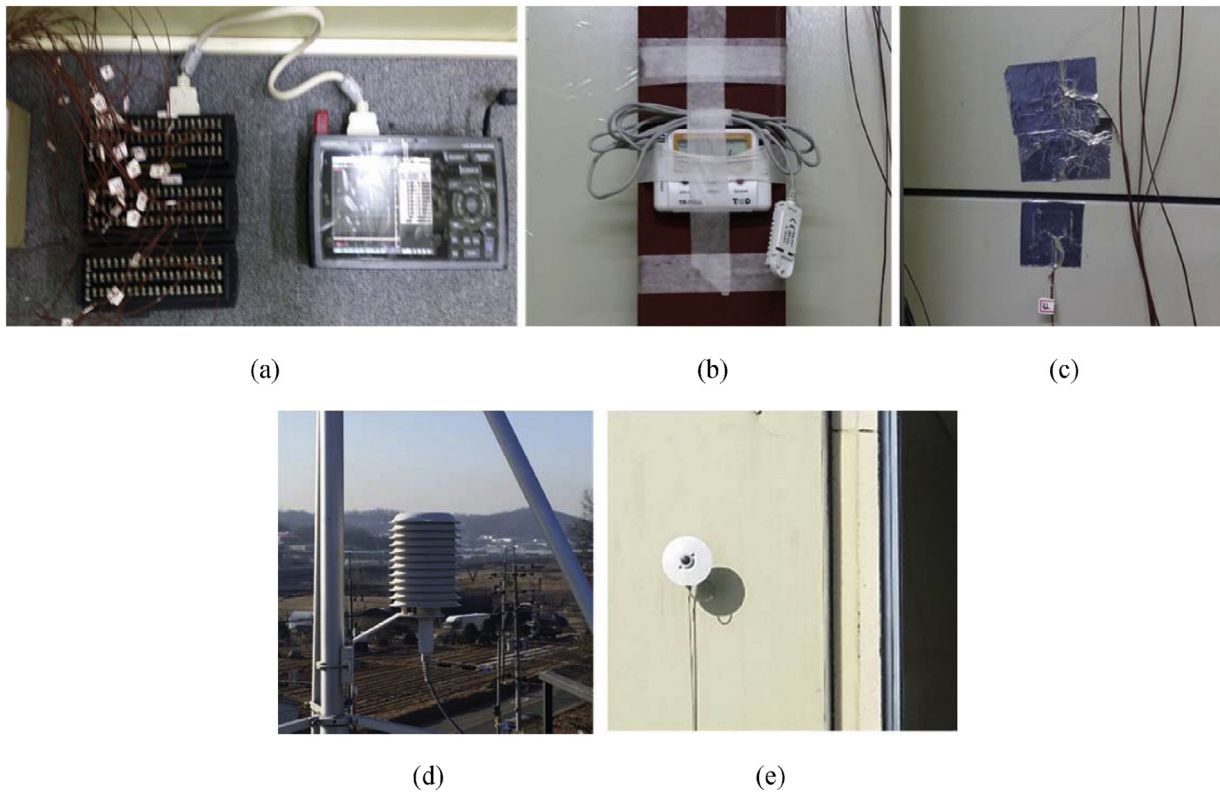


Fig. 15. Installation of measurement equipment: (a) Data logger, (b) Cavity air temperature, (c) Surface temperature, (d) Outdoor air temperature, and (e) Solar radiation incident on the vertical surface.

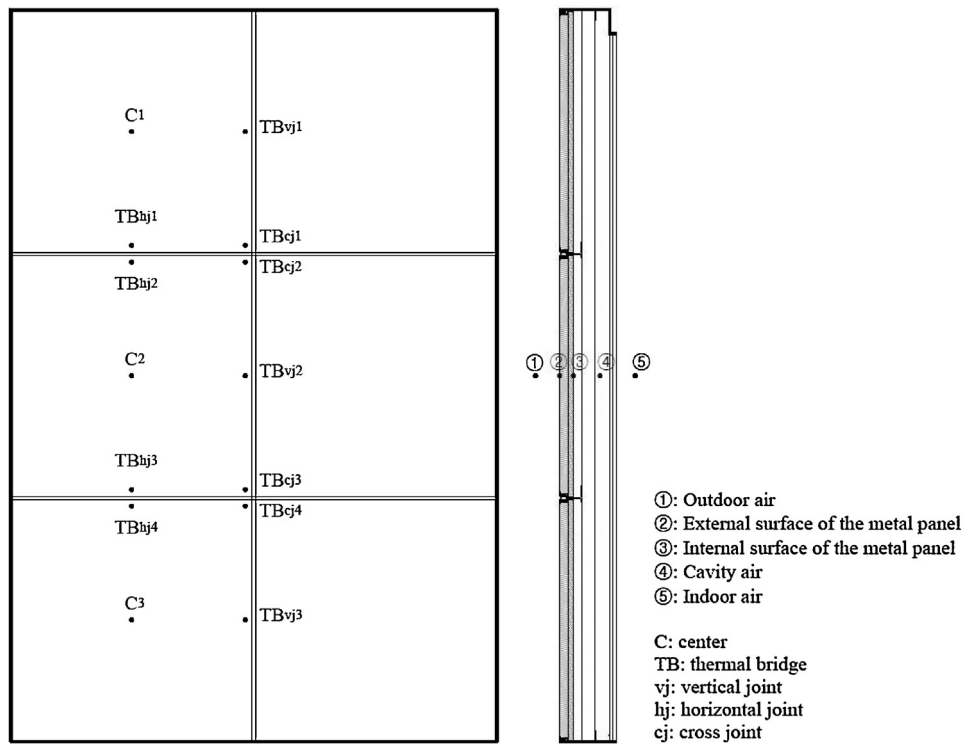


Fig. 16. Temperature measuring locations.

external surface temperatures of the vertical and cross joints were 3.0–4.1 °C lower than that of the existing case, which clearly shows the significant reduction in the effect of the thermal bridges.

4.2.2. Analysis of internal and external surface temperatures of metal panel

4.2.2.1. Distribution of internal and external surface temperatures. Using Eqs. (4) and (5), the averages of the surface temperatures

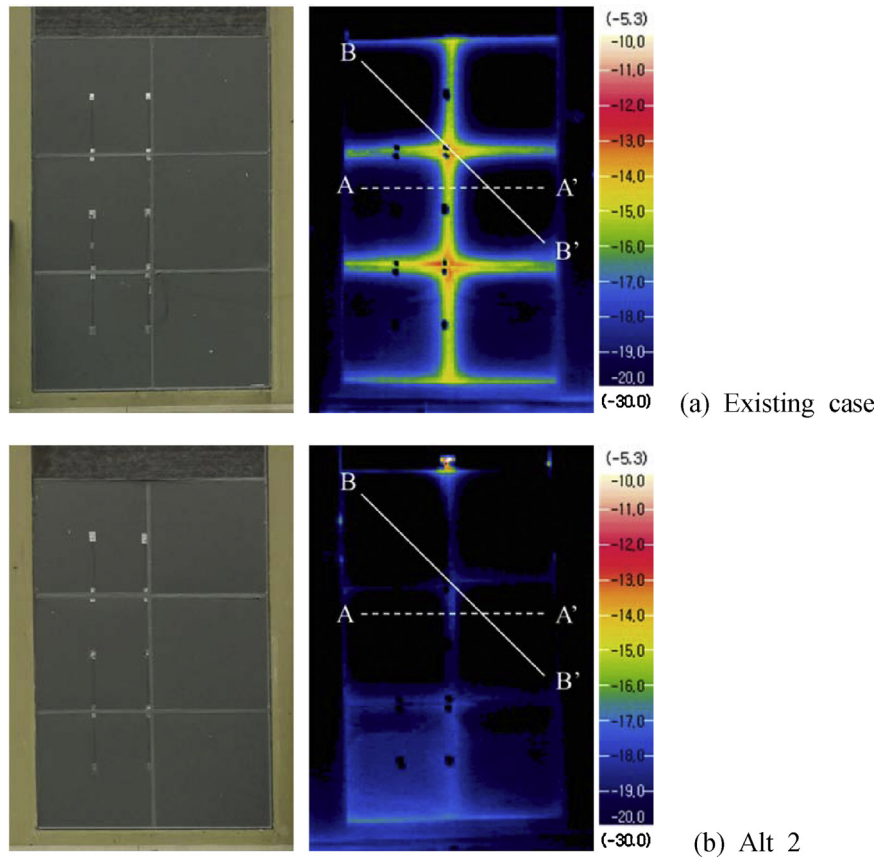


Fig. 17. Infrared thermal images of existing case and Alt 2.

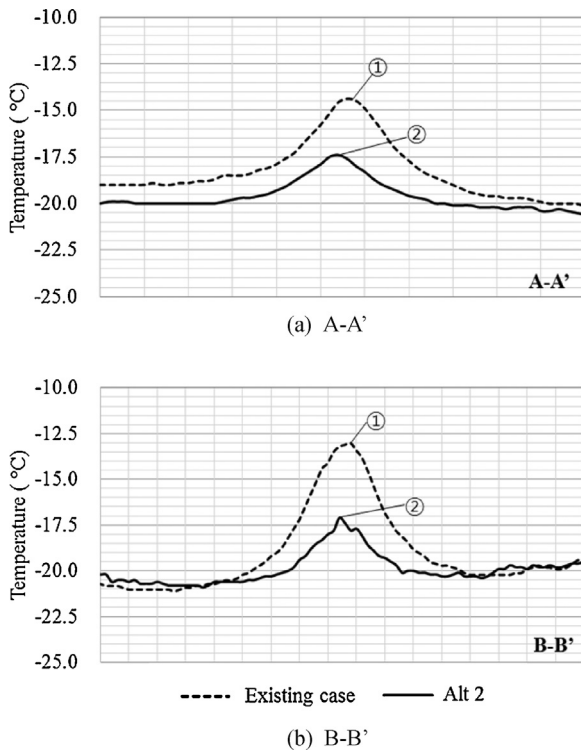


Fig. 18. Surface temperature distributions in infrared thermal images (A-A' and B-B' in Fig. 17).

measured at the center and thermal bridges (vertical, horizontal, and cross joints) of the metal panel were obtained to analyze the distribution of the internal and external surface temperatures in the existing case and Alt 2. Since the surface temperature is affected by the outdoor air temperature and solar radiation, the overall measurement period was divided into night and day depending on whether solar radiation was present. The night-time hours totaled 141.75, which accounted for 59% of the total measurement period. The day-time hours totaled 98.25, accounting for 41% of the total measurement period.

$$\bar{T}_C = \sum_{i=1}^n T_{Ci} / n_C \quad (4)$$

$$\bar{T}_{TBk(k=vj,hj,cj)} = \sum_{i=1}^n T_{TBki} / n_{TBk} \quad (5)$$

Fig. 19 shows the distribution of the internal and external surface temperatures at the center and thermal bridges of the metal panel. The external surface temperature changed in step with the outdoor air temperature during the night and the solar radiation during the day. The internal surface temperature remained relatively constant at about 20 °C (centers of both cases and thermal bridges of Alt 2) and about 10–15 °C (thermal bridges of the existing case) during the night but increased slightly during the day due to the solar heat gain. The internal and external surface temperatures at the center of the metal panel were similar in both the existing case and Alt 2. However, at the thermal bridges they differed significantly between the existing case and Alt 2. The difference between two cases during the night was larger than that during the day.

Table 5 lists the averages, standard deviations, and maximum and minimum values of the internal and external surface tempera-

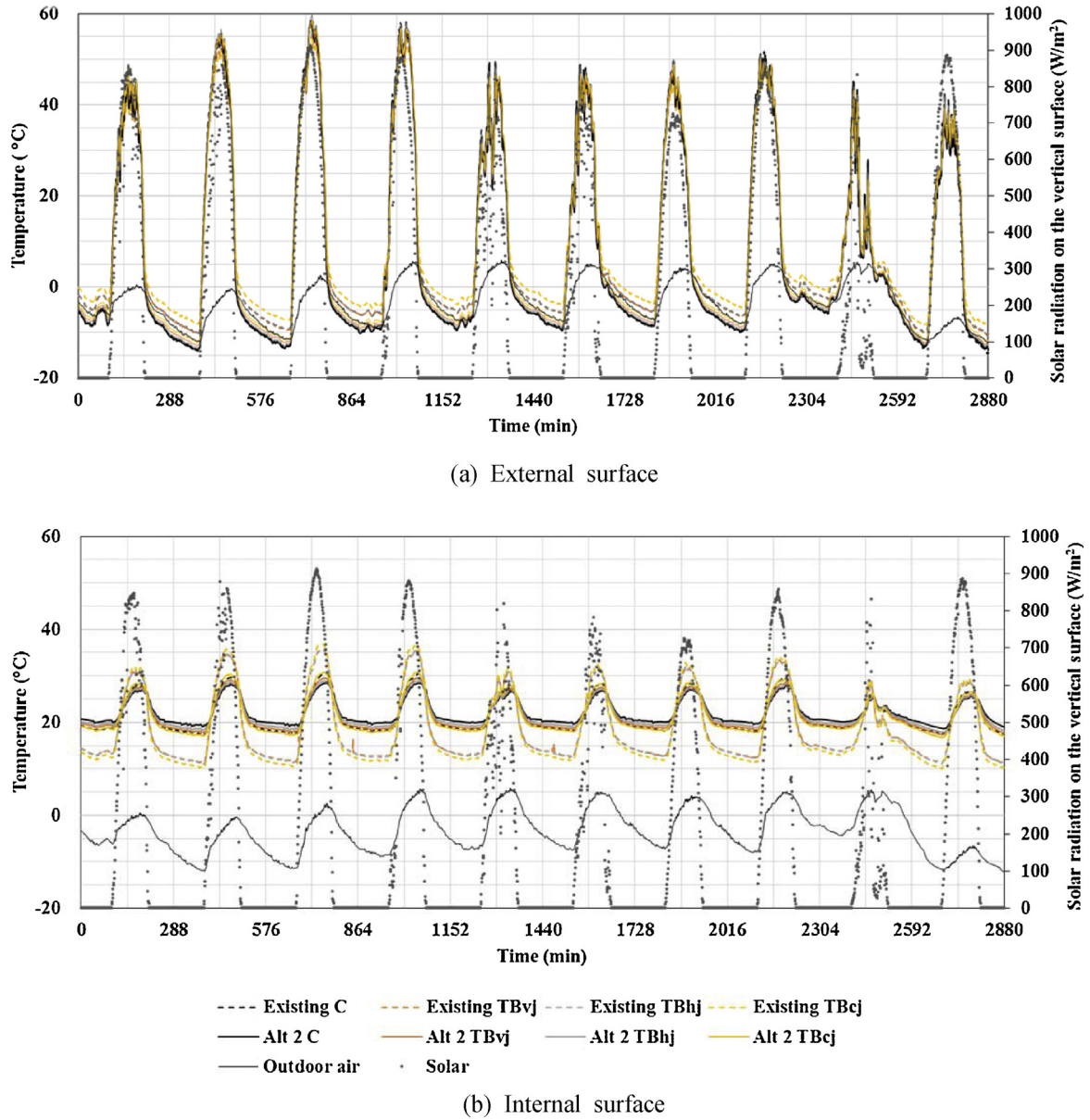


Fig. 19. Average surface temperature distributions.

tures at the center and at the thermal bridges of the metal panel for the total measurement period, for both night and day. The average $\bar{T}_C$ of the external surface during the total period was similar in both cases, while the average $\bar{T}_{TBvj}$, $\bar{T}_{TBhj}$, and $\bar{T}_{TBcj}$ differed in each case. These temperature differences between the existing case and Alt 2 during the night were larger than those during the total period and the day. For the existing case, the average $\bar{T}_C$ was 3.1–4.9 °C lower than the average $\bar{T}_{TBvj}$, $\bar{T}_{TBhj}$, and $\bar{T}_{TBcj}$, while the average $\bar{T}_C$ was 0.5–1.6 °C lower than the average $\bar{T}_{TBvj}$, $\bar{T}_{TBhj}$, and $\bar{T}_{TBcj}$ for Alt 2. This indicates that the heat loss through the thermal bridges at the vertical, horizontal, and cross joints of the metal panels were considerably reduced in Alt 2 compared to the existing case. In particular, the reduction of the point heat loss due to applying the thermally broken bracket at the cross joints was found to be significant.

The temperature differences between the average $\bar{T}_C$ and $\bar{T}_{TBvj}$, $\bar{T}_{TBhj}$, and $\bar{T}_{TBcj}$ during the day were found to be within a range of 1 °C for both the existing case and Alt 2, indicating that there is no significant difference between the existing case and Alt 2. The

maximum $\bar{T}_C$ was approximately 60 °C in both cases during the day because of the absorption of solar heat by the external surface. The maximum $\bar{T}_{TBvj}$, $\bar{T}_{TBhj}$, and $\bar{T}_{TBcj}$ values in Alt 2 were similar to the maximum $\bar{T}_C$, while the maximum $\bar{T}_{TBvj}$, $\bar{T}_{TBhj}$, and $\bar{T}_{TBcj}$ values in the existing case were clearly lower than the maximum $\bar{T}_C$.

The average $\bar{T}_C$ of the internal surface of the existing case during the total period was slightly higher than that of Alt 2, but the difference was not significant. However, the average $\bar{T}_{TBvj}$, $\bar{T}_{TBhj}$, and $\bar{T}_{TBcj}$ for the existing case during the total period were much lower than those of Alt 2. In addition, the standard deviations of $\bar{T}_{TBvj}$, $\bar{T}_{TBhj}$, and $\bar{T}_{TBcj}$ for the existing case were approximately 2.0–2.4 times greater than those of Alt 2. Furthermore, for the existing case, the average $\bar{T}_C$ was 5.2–6.2 °C higher than the average $\bar{T}_{TBvj}$, $\bar{T}_{TBhj}$, and $\bar{T}_{TBcj}$, while the average $\bar{T}_C$ was 0.6–1.7 °C higher than the average $\bar{T}_{TBvj}$, $\bar{T}_{TBhj}$, and $\bar{T}_{TBcj}$ for Alt 2. This means that the thermal bridge effect was significant in the existing case and was considerably reduced in Alt 2. The maximum $\bar{T}_{TBvj}$, $\bar{T}_{TBhj}$, and $\bar{T}_{TBcj}$ values of the existing case were 6.2–6.9 °C higher than those of Alt 2, while the minimum $\bar{T}_{TBvj}$,

Table 5
External and internal surface temperatures of the metal panel by total measurement period, night, and day.

External surface (°C)													Outdoor		
Existing case						Alt 2		Internal surface (°C)					Air (°C)	Solar radiation (W/m²)	
Existing case						Existing case					Alt 2				
$\bar{T}_C$	$\bar{T}_{TBvj}$	$\bar{T}_{TBhj}$	$\bar{T}_{TBcj}$	$\bar{T}_{TBj}$	$\bar{T}_{TBvj}$	$\bar{T}_{TBhj}$	$\bar{T}_{TBcj}$	$\bar{T}_C$	$\bar{T}_{TBvj}$	$\bar{T}_{TBhj}$	$\bar{T}_{TBcj}$	$\bar{T}_C$	$\bar{T}_{TBvj}$	$\bar{T}_{TBhj}$	$\bar{T}_{TBcj}$
Total															
Avg.	7.8	9.4	9.7	10.6	7.5	8.2	8.1	8.7	18.7	18.7	18.2	22.1	21.5	21.8	21.3
SD.	18.30	16.44	16.83	15.72	18.10	17.82	18.23	17.69	6.18	6.18	6.78	2.29	2.91	2.63	3.36
Max.	58.9	54.9	57.9	54.6	58.5	58.2	59.8	58.5	35.7	35.8	37.0	28.5	29.5	28.9	30.8
Min.	-14.6	-10.6	-10.6	-8.4	-14.0	-12.9	-13.5	-12.2	17.1	11.1	9.9	18.6	17.3	17.9	16.7
Night															
Avg.	-6.8	-3.7	-3.7	-1.9	-6.9	-5.9	-6.4	-5.3	19.2	14.0	13.0	20.6	19.5	20.0	18.9
SD.	3.07	2.85	2.83	2.70	3.03	2.98	3.05	2.96	1.03	1.40	1.38	0.76	0.89	0.86	0.91
Max.	3.8	7.2	7.1	8.8	3.9	6.0	5.9	7.4	27.0	23.9	23.5	26.1	25.9	25.8	25.5
Min.	-14.6	-10.6	-10.6	-8.4	-14.0	-12.9	-13.5	-12.2	17.1	11.1	10.0	18.8	17.4	17.9	16.8
Day															
Avg.	28.8	28.3	29.0	28.5	28.3	28.6	29.0	28.9	24.6	25.4	25.6	24.3	24.4	24.3	24.8
SD.	15.21	13.81	14.25	13.36	15.26	15.09	15.47	15.06	3.25	5.61	5.58	6.15	2.89	2.63	3.25
Max.	58.9	54.9	57.9	54.6	58.5	58.2	59.8	58.5	30.6	35.7	37.0	28.5	29.5	28.9	30.8
Min.	-13.0	-9.8	-9.8	-8.1	-13.3	-12.3	-12.9	-11.7	17.1	11.1	9.9	18.6	17.3	17.9	16.1

Table 6
Cavity and indoor air temperatures.

		Existing case (°C)		Alt 2 (°C)	
		Cavity	Indoor	Cavity	Indoor
Total	Avg.	21.8	25.0	22.9	24.7
	SD.	3.32	0.91	1.75	0.96
	Max.	31.3	27.4	27.9	27.7
	Min.	17.4	20.4	20.0	19.9
Night	Avg.	19.4	25.0	21.9	24.8
	SD.	0.89	0.94	0.96	0.65
	Max.	26.8	26.8	26.4	27.0
	Min.	17.5	22.2	20.2	21.8
Day	Avg.	25.1	24.9	24.5	24.6
	SD.	0.92	3.33	0.96	1.89
	Max.	31.3	27.4	27.9	27.7
	Min.	17.4	20.4	20.0	19.9

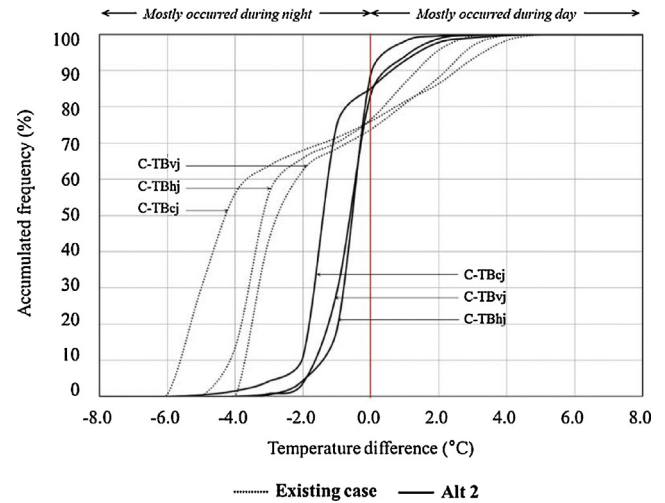


Fig. 20. Accumulated frequency of surface temperature differences between metal panel center and thermal bridges.

$\bar{T}_{TBhj}$, and $\bar{T}_{TBcj}$ values were 6.2–6.9 °C lower. This indicates that the internal surface of the existing case could be easily influenced by the outdoor conditions due to the existence of thermal bridges.

4.2.2.2. Temperature differences between the center and thermal bridges of external surface at the same time. In order to better evaluate the differences between the surface temperatures of the center and the thermal bridges of the metal panel, the temperature difference ($\Delta\bar{T}_{C-TBk}$) between the center and the thermal bridges on the external surface at the same measuring time was calculated by applying Eq. (6). $\Delta\bar{T}_{C-TBk}$ assumes a negative value when the surface temperature at the thermal bridge is higher than that at the center of the metal panel (mostly during the night) whereas it becomes a positive value when the surface temperature at the thermal bridge is lower than that at the center of the metal panel (usually some period during the day when the solar radiation is high).

Fig. 20 shows the accumulated frequency of occurrences of $\Delta\bar{T}_{C-TBk}$ during the total period. If the ideal condition without a thermal bridge in the metal panel is assumed, $\Delta\bar{T}_{C-TBk}$ becomes 0 °C. Thus, as the accumulated frequency distribution approaches the 0 °C line in Fig. 20, the thermal bridging effect decreases. The accumulated frequency distribution for Alt 2 was much closer to the 0 °C line than in the case of the existing case, thus verifying the reduction in the thermal bridging effect of Alt 2. At an accumulated frequency of 25–75%, $\Delta\bar{T}_{C-TBk}$ of the existing case was

Table 7Construction costs of existing case and Alt 2 (Won/m², 1150 Won = 1 USD).

	Existing case	Alt 2
Metal panel material costs	111,800	107,300
Metal panel production costs	10,000	10,000
Material costs for site installation	11,000	11,200
Labor and miscellaneous costs for site installation	41,000	41,000
Total	173,800 (–)	169,500 (–2.5%)

distributed over a range of -5.2 to 0.2 °C whereas $\Delta \bar{T}_{C-TBk}$ for Alt 2 was distributed within a range of -1.7 to -0.2 °C.

$$\Delta \bar{T}_{C-TBk(k=vj,hj,cj)} = \bar{T}_C - \bar{T}_{TBk} \quad (6)$$

4.2.3. Analysis of cavity and indoor temperature

Fig. 21 shows the cavity and the indoor temperature distribution. Table 6 lists their averages, standard deviations, and maximum and minimum values. The average cavity temperatures of the existing case and Alt 2 during the total period were 21.8 °C and 22.9 °C, respectively, 19.4 °C and 21.9 °C during the night, and 25.1 °C and 24.5 °C during the day, showing that the temperature in Alt 2 was 1.5 °C higher during the night and 0.6 °C lower during the day than in the existing case.

The average indoor temperatures with the existing case and Alt 2 during the total period were 25.0 °C and 24.7 °C, respectively, while the standard deviations were 0.91 °C and 0.96 °C, showing that both the existing case and Alt 2 were capable of maintaining nearly the same indoor temperature. Thus, the cavity temperature was mainly determined by the insulation performance of the adjacent metal panel. In Alt 2, the heat loss to the outdoors was reduced during the night so that the cavity temperature remained higher than in the existing case, whereas it was lower than the existing case during the day due to the reduced solar heat gain through the metal panel.

5. Evaluation of economic feasibility through life cycle costs (LCCs)

In order to evaluate the economic feasibility of the existing case and Alt 2, their construction costs and annual energy costs were calculated, and their LCCs were compared. Based on the costs data of the company specialized in metal panel curtain wall systems, the construction costs per unit area were calculated. A three-dimensional unsteady-state heat transfer simulation for the same region as that shown in Fig. 9 was conducted to calculate the annual heat loss and gain per unit area. Also, the validity of the simulated results was investigated by comparing them to the mock-up test results. In addition, heating and cooling energy uses were calculated by taking the efficiency of the heating and cooling system into consideration, and the price of the heating and cooling energy source was taken into consideration to calculate the annual energy costs per unit area. Using the construction costs and annual energy costs per unit area, the LCCs for the sample building over 20, 30, and 40 years were calculated and analyzed.

5.1. Calculation and analysis of construction costs

The construction costs per unit area were divided into the metal panel material and production costs, the material costs for site installation, and the labor and miscellaneous costs for site installation, as listed in Table 7. The metal panel material and production costs included all related costs: for example, the material costs of the steel sheets, aluminum moldings, insulation, etc. and the costs for assembling the metal panels. The material costs for site instal-

lation included material costs such as the steel trusses and brackets while the labor and miscellaneous costs for the site installation included the labor costs, the cost of joint sealing between panels, and the site management costs.

Compared to the existing case, the amount of the aluminum molding was reduced while the amount of PVC-foam pads was increased in Alt 2. Because the reduction in the aluminum molding costs was much larger than the increase in the PVC-foam pad costs, the material costs of Alt 2 were reduced by 4500 Won/m². In addition, the thermally broken bracket of Alt 2 led to the material costs for the site installation increasing by 200 Won/m² relative to the existing case. Thus, the total construction costs per unit area of Alt 2 were reduced by 2.5% overall relative to that of the conventional design.

5.2. Calculation and analysis of annual energy costs

5.2.1. Calculation, validation, and analysis of annual heat loss and gain

5.2.1.1. Calculation of annual heat loss and gain. Physibel Voltra 8.0w, a three-dimensional, unsteady-state heat transfer simulation program, was used to calculate the annual heat loss and gain for the region, as shown in Fig. 9. The time step of the calculation was one hour, and the indoor and outdoor boundary conditions are shown in Fig. 22. The sol-air temperature was applied for the outdoor temperature boundary condition to take the solar radiation into account. The sol-air temperature was calculated by using Eq. (7), as proposed by ASHRAE [41] and we assumed a south-facing vertical wall located 10 m above the ground for the sol-air temperature calculation.

In Eq. (7), the solar absorptance (α) value of 0.8 for the weathered sheet metal was obtained from [41]. The hemispherical emittance (ϵ) value of the external surface was set to 0.66 for the sheet steel, obtained from [40]. The standard weather data for Seoul [42], provided by the Korean Solar Energy Society, was used. The direct and diffuse solar radiations in the weather data were used for the calculation of the incident solar radiation on the vertical surface. The outdoor surface heat transfer coefficients were calculated by using Eq. (8) as proposed by the EnergyPlus engineering reference [43]. The wind speed in Eq. (8) was taken from the weather data. For indoor temperatures, winter (December–February) 20 °C, summer (June–August) 26 °C, spring and fall (March–May and September–November) 23 °C were applied, as specified in the Korean Code for Energy-Efficient Building Design [22]. For the indoor surface heat transfer coefficient, the values provided in the above Code [22] were applied. Other load factors such as ventilation, infiltration, solar heat gain through windows, and internal heat gain were not considered in this simulation. Table 2 lists the material properties applied to the heat transfer simulation.

$$T_{sol} = T_o + \alpha E_t / h_o - \epsilon \Delta R / h_o \quad (7)$$

$$h_o = D + EV + FV^2 \quad (8)$$

5.2.1.2. Validation of three-dimensional unsteady-state heat transfer simulation. To investigate the validity of the heat transfer simulation with the sol-air temperature, additional hourly simulation was conducted for three days during the mock-up test period by modeling the specimen of the existing case (see Fig. 13). The sol-air temperatures were calculated using the outdoor air temperature and the incident solar radiation on the vertical surface measured during the corresponding days in the mock-up test, while the outdoor surface heat transfer coefficients were calculated using the outdoor wind speeds measured in the mock-up test. For the indoor temperature, the measured values were applied.

With regard to the average temperature of six points on the internal and external surface on the second metal panel from the

5.2.1.3. Analysis

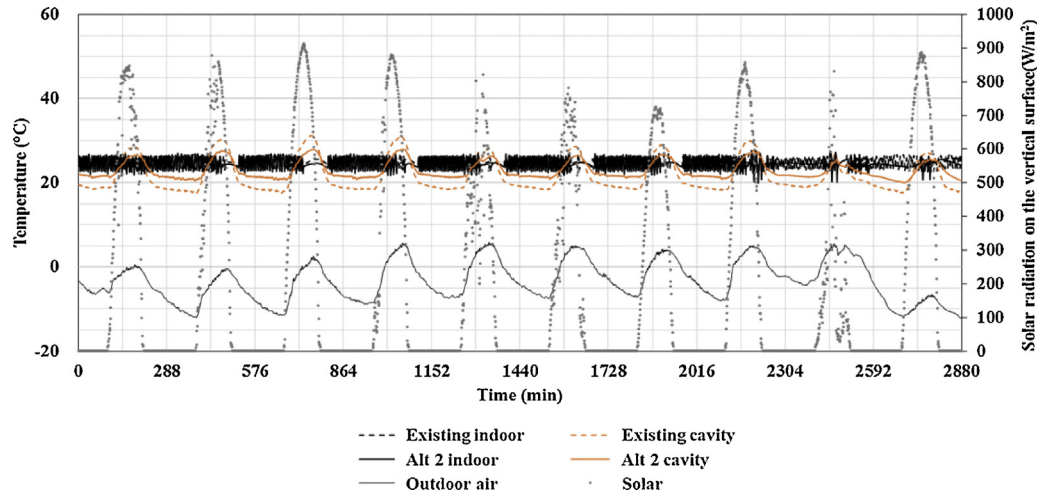


Fig. 21. Cavity and indoor air temperature distributions.

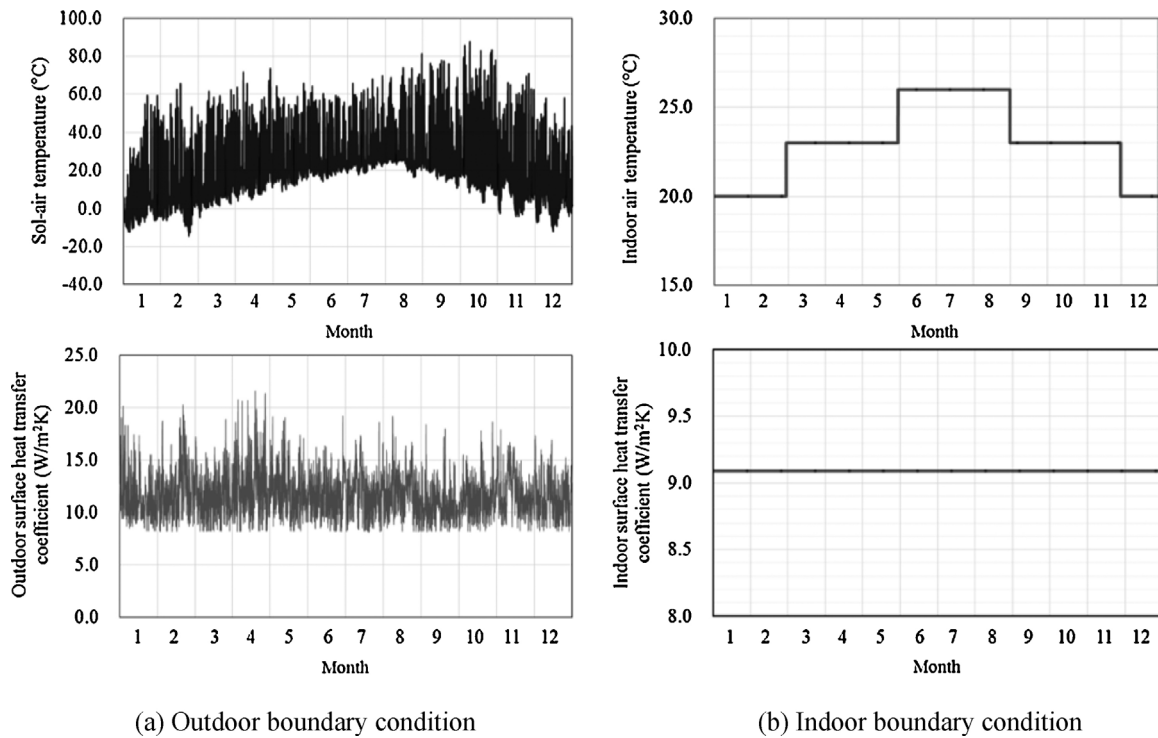


Fig. 22. Boundary conditions for unsteady-state heat transfer simulations.

top (see Fig. 16), the simulated and measured results were compared as shown in Fig. 23. For the external surface, the simulated and measured results showed a highly similar distribution, with an average absolute deviation between the simulated and measured results of 1.9°C , and a normalized mean bias error (NMBE) [44] of 6.0%. For the internal surface, the simulated and measured results also similarly distributed, with an average absolute deviation between them of 2.2° and an NMBE of 7.0%. These deviations were mainly due to differences in the physical properties of the materials and local differences in the indoor and outdoor surface heat transfer coefficients between the simulation and the mock-up test. Considering that the overall distribution was very similar despite these deviations, and if the NMBE was less than 10%, it was regarded as being reliable [44], the heat transfer simulation applying the sol-air temperature can provide valid results that reflect the effect of the solar radiation on the walls.

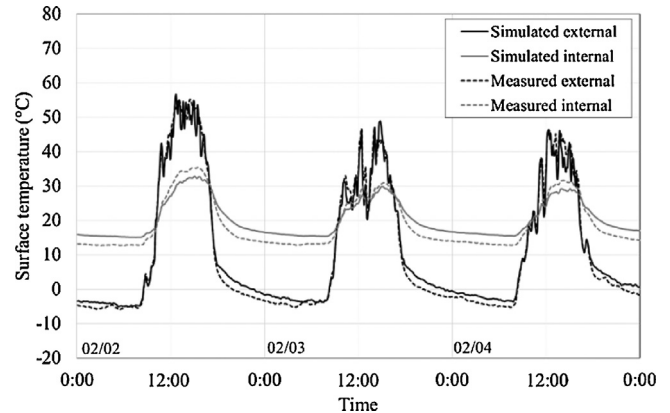


Fig. 23. Comparison of simulated and measured average surface temperatures.

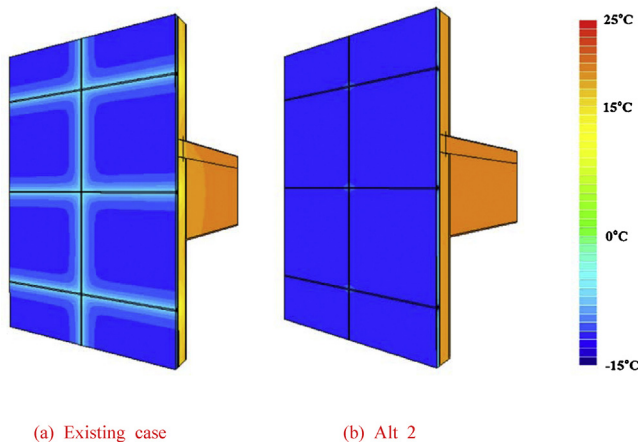


Fig. 24. Temperature distributions of existing case and Alt 2 for the lowest annual sol-air temperature.

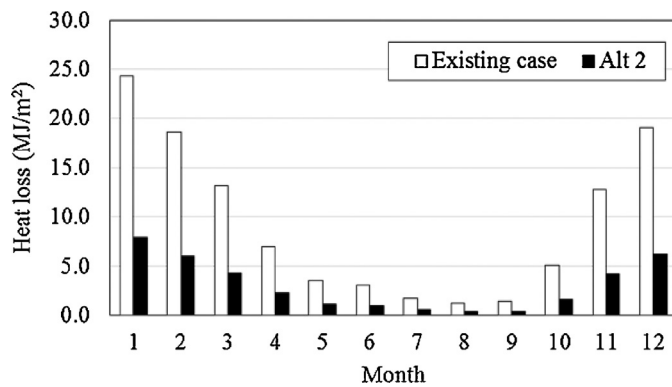


Fig. 25. Monthly heat losses of existing case and Alt 2.

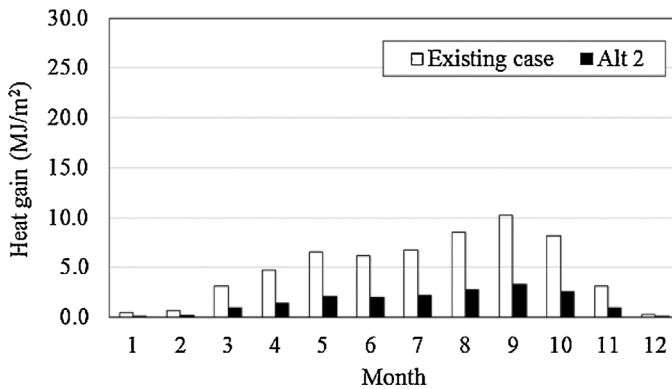


Fig. 26. Monthly heat gains of existing case and Alt 2.

Fig. 24 shows the temperature distributions of the existing case and Alt 2 for the lowest annual sol-air temperature. The annual heat loss and gain per unit area of the existing case and Alt 2 are shown in Figs. 25 and 26. The annual heat loss of the existing case was 110.9 MJ/m² while that of Alt 2 was 36.0 MJ/m², which was reduced by 67.5%. The annual heat gain was about half of the annual heat loss. The annual heat gain of the existing case was 59.0 MJ/m² and that of Alt 2 was 18.7 MJ/m², which was reduced by 68.2%. These results show that both the heat loss and gain are reduced at a similar rate.

The monthly heat loss was largest in January for both the existing case and Alt 2, while the monthly heat gain was largest in September. In January, the outdoor air temperature was the lowest,

Table 8
Seasonal COP of electric heat pump.

	Heating mode	Cooling mode
Heating and cooling power	23.0 kW	22.0 kW
Electricity consumption	6.4 kW	7.2 kW
COP	3.6	3.1

leading to the heat loss being the largest. In September, meanwhile, the solar radiation was large and the outdoor air temperature was relatively high compared to the indoor temperature, even at night, such that the heat gain was the largest. Between December and February, when the heat loss was significantly high, the heat gain was no more than 1–4% of the heat loss. This heat gain occurred due to an increase in the external surface temperature caused by the solar radiation during the day. Between July and September, when the heat gain was much higher than the heat loss, the heat loss was around 13–25% of the heat gain. This heat loss occurred during the night when the outdoor air temperature was lower than indoors.

5.2.2. Calculation and analysis of annual energy costs

An electric heat pump (EHP) was assumed to be used as the heating and cooling system. An EHP offers convenient operation and maintenance in comparison with central plant and air-conditioning systems; this system is widely applied in Korea as the heating and cooling system of small- and medium-size buildings [45]. The coefficient of performance (COP) of an EHP was applied based on the EHP performance data provided by the manufacturer, as listed in Table 8. The heating and cooling energy uses were calculated using Eqs. (9) and (10), dividing the heat loss and gain per unit area by the COPs of heating and cooling modes. Two assumptions were applied, as follows: first, the heating period was from November to April when the heat loss was larger than the heat gain, while the cooling period was from May to October when the heat gain was larger than the heat loss. Second, the heating and cooling energy uses were calculated with respect to the heat loss only during the heating period, and with respect to the heat gain only during the cooling period, respectively.

$$E_h = Q_h / \text{COP}_{\text{EHP}_h} \quad (9)$$

$$E_c = Q_c / \text{COP}_{\text{EHP}_c} \quad (10)$$

To determine the annual energy costs, seasonal and hourly electricity rates [46] provided by the Korean Electric Power Corporation (KEPCO) were applied using Eq. (11). The electricity rates listed in Table 9 were applied to office buildings with a contracted demand of 300 kW or higher. In Eq. (11), 1.137 is a constant reflecting the tax levied on electricity. The demand charges were not considered in the energy costs calculation.

$$\text{Cost}_{\text{en}} = \sum_{m=1}^{12} (E_m \times \text{Rate}_m) \times 1.137 \quad (11)$$

The heating and cooling energy uses and costs for the existing case and Alt 2 are listed in Table 10. Since electricity rates differ seasonally and hourly, the energy uses and costs are not proportional to each other. The annual energy uses and energy costs of the existing case were 11.49 kWh/m²/year and 1373 Won/m²/year while those of Alt 2 were 3.66 kWh/m²/year and 440 Won/m²/year, indicating that the energy costs for Alt 2 were 68% lower than those for the existing case.

5.3. Analysis of LCCs for sample building

A 10-story office building with a total floor area of 12,000 m² was considered. The total area of the external walls was 2972 m² (see

Table 9Electricity rates (Won/kWh, 1150 Won $\approx$ 1 USD).

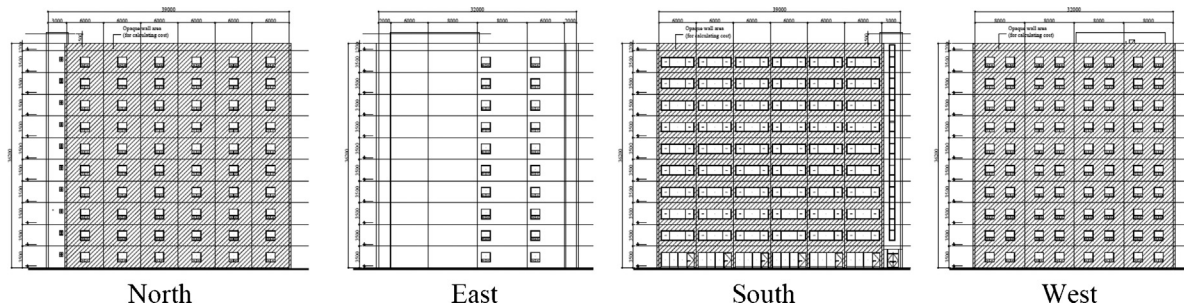
Type (general service)		Summer (June to August)	Spring, fall (March to May and September to October)	Winter (November to February)
High-Voltage A option I ^a (more than 300 kW)	Off-peak load	61.6	61.6	68.6
	Mid-load	114.5	84.1	114.7
	Peak-load	196.6	114.8	172.2

^a Time-period classification: (summer, spring, fall) off-peak load 23:00–09:00, mid-load 09:00–10:00, 12:00–13:00, 17:00–23:00, peak-load 10:00–12:00, 13:00–17:00 (winter) off-peak load 23:00–09:00, mid-load 09:00–10:00, 12:00–17:00, 20:00–22:00, peak-load 10:00–12:00, 17:00–20:00, 22:00–23:00

Table 10

Heating and cooling energy uses and costs of existing case and Alt 2.

Period	Month	Existing case		Alt 2	
		Energy use (kWh/m ²)	Energy costs (Won/m ²)	Energy use (kWh/m ²)	Energy costs (Won/m ²)
Heating	11	0.99	106	0.32	35
	12	1.47	169	0.48	56
	1	1.87	218	0.61	72
	2	1.44	164	0.47	53
	3	1.02	84	0.33	28
	4	0.54	43	0.17	15
	Sum	7.33	785	2.38	259
Cooling	5	0.59	67	0.19	20
	6	0.55	99	0.18	30
	7	0.60	103	0.20	32
	8	0.77	132	0.25	41
	9	0.92	102	0.30	32
	10	0.73	85	0.23	26
	Sum	4.16	589	1.28	181
Total		11.49 (–)	1373 (–)	3.66 (–68.1%)	440 (–68.0%)

**Fig. 27.** Elevations of sample building used for calculation of external non-vision wall area.**Table 11**

Life cycle costs of existing case and Alt 2.

Life time (years)	Case	Construction costs (10 ³ Won)	Annual energy costs (10 ³ Won/year)	Life cycle costs (10 ³ Won)
20	Existing case	516,521	4,081	570,094 (–)
	Alt 2	503,741	1,307	520,904 (–8.6%)
30	Existing case	516,521	4,081	583,822 (–)
	Alt 2	503,741	1,307	525,302 (–10.0%)
40	Existing case	516,521	4,081	592,749 (–)
	Alt 2	503,741	1,307	528,162 (–10.9%)

Fig. 27). After multiplying the wall area (A_{wall}) by the construction costs ($Cost_{con}$) and annual energy costs ($Cost_{en}$) per unit area, the LCCs of the existing case and Alt 2 for lifetimes (n) of 20, 30, and 40 years were calculated using Eqs. (12) and (13). The inflation rate (i), used to calculate the present worth coefficient (PW), was 1.2%, which was the average increase in the electricity rates from 2005 to 2014, as specified in the Economic Statistics System published by the Bank of Korea [47]. The interest rate (R) was 5.65%, which was the average interest rate on a loan from 2005 to 2014, as specified in the above [47]. The LCCs are shown in Table 11. The LCCs for Alt 2 for lifetimes of 20, 30, and 40 years were reduced by 8.6%,

10.0%, and 10.9%, respectively, relative to that of the existing case and the corresponding reductions in costs were 49,190 thousand Won, 58,520 thousand Won, and 64,587 thousand Won. From these results, the cost effectiveness of Alt 2 can be verified.

$$LCC = Cost_{con} \times A_{wall} + PW \times Cost_{en} \times A_{wall} \quad (12)$$

$$PW = \left[\frac{1+i}{1+R} \times \left(\left(\frac{1+i}{1+R} \right)^n - 1 \right) \right] / \left(\frac{1+i}{1+R} - 1 \right) \quad (13)$$

6. Conclusions

In this study, alternatives for reducing linear and point thermal bridges in steel truss metal panel curtain wall systems were proposed, and three-dimensional steady-state heat transfer simulations and mock-up tests were conducted to evaluate the insulation performance of alternatives. With the construction costs and the annual energy costs calculated through three-dimensional unsteady-state heat transfer simulations, the life cycle costs of the existing case and the selected alternative were calculated and compared. This study is summarized as follows.

- To reduce the linear thermal bridges in the joints between the metal panels of conventional systems, alternatives were proposed in which the length of the aluminum molding at the sides of a metal panel was reduced and an additional polyurethane thermal breaker was inserted. Furthermore, to reduce the point thermal bridges caused by the aluminum brackets, a polyurethane thermal breaker was inserted into the existing aluminum brackets. With regard to a typical external wall area, three-dimensional steady-state heat transfer simulations were conducted with the existing case and three alternatives. As results, Alt 2 was selected as the most effective alternative. Alt 2 was found to reduce the overall heat loss and effective U-factor by 68.0% compared to the existing case.
- In the mock-up tests performed in winter, the average external surface temperature at the thermal bridge of the existing case was 3.1–4.9 °C higher than that at the center of the metal panel during the night. On the other hand, the average external surface temperature at the thermal bridge of Alt 2 was 0.5–1.6 °C higher than that at the center. The average internal surface temperature at the thermal bridge of the existing case was 5.2–6.2 °C lower than that at the center whereas that at the thermal bridge of Alt 2 was 0.6–1.7 °C lower than that at the center. Therefore, we confirmed that the thermal bridging effect of Alt 2 was significantly reduced. In particular, the application of a thermally broken bracket was found to be effective for reducing the point thermal bridge.
- Alt 2 reduced the construction costs by 2.5% relative to the existing case by reducing the length of the aluminum molding at the sides of a metal panel, and also reduced the annual heating and cooling energy costs by 68.0% relative to the existing case. Life cycle costs analysis results for the sample building showed that Alt 2 reduced the life cycle costs by 8.6% (over 20 years) to 10.9% (over 40 years) relative to the existing case.

As mentioned above, reducing thermal bridges is not only feasible but also cost effective for conventional metal panel curtain wall systems. To realize the zero-energy buildings that many countries are carrying forward as a policy target, thermal bridge-free construction is an important issue. Therefore, it is important to develop various types of thermal breaking products suitable for various types of thermal bridges.

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References

- [1] Ministry of Land, Infrastructure and Transport (MOLIT), in: Current Status of Green Building-related Legislations and Driving Direction, Korean Institute of Architectural Sustainable Environment and Building Systems 2013 Seminar Presentation Material, Republic of Korea, 2013.
- [2] Korea Energy Economics Institute (KEEI), Energy Consumption Survey, Ministry of Knowledge Economy, Republic of Korea, 2012.
- [3] National Roadmap to Achieve Greenhouse Gas Reduction Target, Presidential Committee on Green Growth, Republic of Korea, 2014.
- [4] S. Song, B. Koo, J. Lim, Comparison of annual heating and cooling energy demands of internally and externally insulated apartment buildings considering the thermal bridging effect and the heat capacity difference using monthly calculation method of ISO 13790, *J. Archit. Inst. Kore. Plan. Des. Sect.* 26 (7) (2010) 321–332.
- [5] B. Koo, J. Lim, S. Song, Current status and improvement schemes of regulations related to thermal bridges in residential buildings, *Autumn Proce. Archit. Inst. Korea* 31 (2) (2011) 461–462.
- [6] S. Song, M. Yeo, B. Koo, S. Lee, Energy efficiency analysis of internally and externally insulated apartment buildings, *J. Asian Archit. Build. Eng.* 10 (2) (2011) 453–459.
- [7] M. Park, J. Song, S. Park, J. Lim, S. Song, Influence of thermal bridging effects on the insulation performance of external walls covered with metal panels and stones, *Spring Proc. Archit. Inst. Korea* 34 (1) (2014) 179–180.
- [8] T.G. Theodosiou, A.G. Tsikaloudaki, K.J. Kontoleon, D.K. Bikas, Thermal bridging analysis on cladding systems for building facades, *Energy Build.* 109 (2015) 377–384.
- [9] S. Song, J. Yi, B. Koo, Insulation plan of aluminum curtain wall-fastening unit for high-rise residential complex, *Build. Environ.* 43 (2008) 1310–1317.
- [10] H. Seok, J. Jung, H. Kwak, S. Song, A study on the heat transmission performance of stone finished curtain wall system through the mock-up test, *J. Archit. Inst. Korea Plan. Des. Sect.* 22 (8) (2006) 259–266.
- [11] Y. Yu, Study on Predicting the Thermal Insulating Performance of Steel Stud Drywalls, Yonsei University Doctoral Thesis, The Republic of Korea, 2008.
- [12] J. Kosny, J.E. Christian, Thermal evaluation of several configurations of insulation and structural materials for some metal stud walls, *Energy Build.* 22 (2) (1995) 157–163.
- [13] E. de Angelis, E. Serra, Light steel-frame walls: thermal insulation performances and thermal bridges, *Energy Procedia* 45 (2014) 362–371.
- [14] Y.J. Kim, A. Allard, Thermal response of precast concrete sandwich walls with various steel connectors for architectural buildings in cold regions, *Energy Build.* 80 (2014) 137–148.
- [15] T.G. Theodosiou, A.M. Papadopoulos, The impact of thermal bridges on the energy demand of building with double brick wall constructions, *Energy Build.* 40 (11) (2008) 2083–2089.
- [16] M. Kuhnhenner, Energetische Qualität von Gebäudehüllen in Stahl-Sandwichbauweise, in: Ph.D. Thesis, RWTH Aachen University, Germany, 2010.
- [17] M. Gorgolewski, Developing a simplified method of calculation U-values in light steel framing, *Build. Environ.* 42 (2007) 230–236.
- [18] S.M. Doran, M.T. Gorgolewski, U-values for Light Steel-frame Construction, BRE, 2002.
- [19] T. Ward, IP 10/02 Metal Cladding: Assessing the Thermal Performance of Built-up Systems Which Use 'Z' Spacers, BRE, 2002.
- [20] M.T. Gorgolewski, Metal Cladding: U-value Calculation, The Steel Construction Institute, 2002.
- [21] K. martin, C. Escudero, A. Erkoresh, I. Flores, J.M. Sala, Equivalent wall method for dynamic characterization of thermal bridges, *Energy Build.* 55 (2012) 704–714.
- [22] The Code for Energy-efficient Building Design, Ministry of Land, Infrastructure and Transport (MOLIT), Republic of Korea, 2013.
- [23] 2015 International Energy Conservation Code, International Code Council, 2015.
- [24] ASHRAE Standard 90.1—Energy Standard for Buildings except Low-Rise Residential Buildings (2013).
- [25] G. Mao, Thermal bridges, in: Efficient Models for Energy Analysis in Buildings, Department of Building Sciences, unglia Tekniska Högskolan, Stockholm, 1997.
- [26] B. Koo, J. Lim, S. Song, Analysis of insulation performance degradation due to thermal bridge by the U-value levels of internally and externally insulated walls, *Autumn Proc. Korean Inst. Archit. Sustain. Environ. Build. Syst.* (2012) 87–90.
- [27] J. Song, S. Park, M. Park, J. Lim, S. Song, Influence of thermal bridges on the insulation performance of curtain wall panel systems, *J. Asian Archit. Build. Eng.* 14 (3) (2015) 741–748.
- [28] Gen 2015—Integrated System for Building and General Structures, MIDAS Information Technology Co., Ltd, 2015.
- [29] Test Report—Structural Analysis for Anchor System, CITYWALL ENG Co., Ltd, 2015.
- [30] Korean Building Code and Commentary, Architectural Institute of Korea (AIK), 2009, 2016.
- [31] Physibel Trisco Manual, Physibel, 2010.
- [32] S. Song, A study on the method for determining the extent of insulation to prevent the inside surface condensation at thermal bridge, *J. Archit. Inst. Korea* 14 (10) (1998) 275–284.
- [33] ISO 10211—Thermal Bridges in Building Construction -Heat Flows and Surface Temperatures -Detailed Calculations, International Organization for Standardization, 2007.

[1] Ministry of Land, Infrastructure and Transport (MOLIT), in: Current Status of Green Building-related Legislations and Driving Direction, Korean Institute of

- [34] A. Binz, et al., Vacuum Insulation in the Building Sector: Systems and Applications, IEA/ECBCS Annex 39 High Performance Thermal Insulation Systems (HiPTI), 2005.
- [35] S. Park, B. Choi, J. Lim, S. Song, Evaluation of mechanically and adhesively fixed external insulation systems using vacuum insulation panels for high-rise apartment buildings, *Energies* 7 (9) (2014) 5764–5786.
- [36] H. Sallee, D. Quenard, E. Valenti, M. Galan, VIP as thermal breaker for internal insulation system, *Energy Build.* 85 (2014) 631–637.
- [37] IP1/06—Assessing the Effects of Thermal Bridging at Junctions and Around Openings, Building Research Establishment (BRE), 2006, 2016.
- [38] Dutch Building Code Online <http://www.bouwbesluitonline.nl>.
- [39] DIN 4108-2:-03, Wärmeschutz und Energie—Einsparung in Gebäuden. Teil 2: Mindestanforderungen an den Wärmeschutz, Deutsches Institut für Normung, Berlin, 2001, pp. 2001.
- [40] Table of Emissivity of Various Surfaces for Infrared Thermometry, MIKRON Instrument Company, Inc, 2003.
- [41] ASHRAE Handbook Fundamental, ASHRAE, 2009, pp. 18.22–18.23.
- [42] Standard Weather Data Set of Seoul, The Korean Solar Energy Society, 2015 <http://www.kses.re.kr>.
- [43] Engineering References, EnergyPlus, 2014, pp. 64–75.
- [44] ASHRAE Guideline 14–2002, Measurement of Energy and Demand Savings, ASHRAE, 2002.
- [45] O.J. Kwon, Evaluating efficiency of electric heat pumps under partial-load, in: Master's Thesis, Han Yang University, Republic of Korea, 2012.
- [46] Korea Electric Power Corporation (KEPCO), <http://www.kepco.co.kr>.
- [47] Economic Statistics System of the Bank of Korea, <http://ecos.cok.or.kr>.