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Energy Performance Evaluation for Exterior Insulation System Consisting of Truss-Form Wire-Frame Mullion Filled with Glass Wool

Jin-Hee Song [1], Cheol-Yong Park [2] and Jae-Weon Jeong [2,*]

[1] Lotte Engineering & Construction, 50-2 Jamwon-dong, Seocho-gu, Seoul 06515, Korea; jinheesong5@lotte.net

[2] Department of Architectural Engineering, College of Engineering, Hanyang University, Seoul 04763, Korea; fnmlove@naver.com

* Correspondence: jjwarc@hanyang.ac.kr; Tel.: +82-2-2220-2370

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Abstract: Heat loss and gain through opaque envelopes of buildings are major factors that affect the overall cooling and heating loads in buildings. The government has enforced regulations to strengthen the thermal transmittance requirement level as a major means of reducing greenhouse gas emissions in the building sector. In addition, the thermal bridge is considered to be one of the major factors in heating load of buildings. In this study, truss-form wire frame was developed in order to minimize thermal bridge of steel mullion in exterior insulation system. In the case of thermal transmittance test for specimen of 0.145 W/m^2 K as design value, the value of the steel pipe was 0.190 W/m^2 K and the value of the truss-form wire frame was 0.150 W/m^2 K, respectively. This means the other is much smaller than the one in thermal bridge. For four cases, annual energy performance analysis was calculated using Passive House Planning Package (PHPP)—ideal condition without thermal bridge, steel pipe mullion without insulation in the rear side, steel pipe mullion with insulation in the rear side, and truss-form wire-frame mullion filled with glass wool. As results, the annual heating energy demands were 15.68 kWh/m^2, 25.42 kWh/m^2, 16.78 kWh/m^2, and 16.09 kWh/m^2, respectively.

Keywords: thermal bridge; truss insulation frame; dry exterior insulation system; building envelope performance; energy performance

1. Introduction

1.1. Background and Objective

Heat loss and gain through opaque envelopes of buildings, such as walls and roofs, are major factors that affect the overall cooling and heating loads in buildings. According to a previous study, the proportions are, respectively, 35% and 32% for heating and cooling of residential buildings, and 46% for the heating energy of commercial buildings [1]. The Korean government has proposed regulations to strengthen the thermal transmittance requirement level as a major means of reducing greenhouse gas emissions in the building sector, and it gradually strengthened the design standards in order to realize energy saving in buildings [2]. Accordingly, the design standards of energy saving for buildings were again strengthened in September 2018. For residential houses in the Central I Region of Korea, the maximum required levels of thermal transmittance for external walls and windows are; 015; W/m^2, K. and 0.9 W/m^2 K, respectively. Meanwhile, for nonresidential houses, the corresponding maximum values are 0.17 W/m^2 K and 1.3 W/m^2 K [3].

In addition, the thermal bridge is considered to be one of the major considerations in heating loads of buildings. The heat loss due to the thermal bridge can, therefore, be reduced by changing the previous scoring method involving the energy performance index in the energy saving plan according to the application area of exterior insulation. The scoring method was changed to a new scoring method that discriminates a score depending on the construction details in the thermal bridge portions by presenting a linear thermal transmittance for each thermal bridge portion. As per the related regulations, the thermal bridge is limited, occurring in major structural joints, which can be minimized primarily by employing exterior insulation [4].

For exterior insulation, various construction methods exist based on the insulation materials and finish materials. These methods are largely classified as wet or dry construction methods. The wet exterior insulation system generally refers to the processing of the surface finish, i.e., methods such as using paints, by coating base-coating materials on the insulation material's surface after applying the insulation material to the concrete wall. This approach is used in a limited scope in concrete wall-type buildings. The dry exterior insulation system refers to a method of fixing exterior materials, such as stones and metals, using brackets after fixing insulation materials between lattices, which are made of vertical and horizontal members, such as square pipes and C channels. These are built in advance to fix insulation materials and finish materials. This approach has been widely applied in curtain wall buildings of various sizes, lower stories in apartments, subsidiary facilities, etc.

For dry exterior insulation systems, metal-fixing ironware, such as vertical and horizontal members, brackets, and anchor bolts, which are used to fix insulation materials and exterior materials, was penetrated through insulation materials, to form a thermal bridge. Several studies have analyzed thermal bridge effects due to fixing ironware in dry exterior insulation systems. Koo et al. [5] and Theodosiou et al. [6] quantitatively evaluated the heat loss through a thermal bridge that was formed during the construction of exterior materials, such as stone curtain walls and metal cladding, and they proposed improvements. Kosny and Kossecka [7] reported that the total insulation performance was degraded by around 40–50% if there was a thermal bridge through metal members such as metal curtain walls and complex envelopes. Song et al. [8] reported that the effective thermal transmittance of metal and stone exterior insulation systems could be more than three times larger than the legally required thermal transmittance even if the legal thermal transmittance requirements are met during the exterior insulation construction of concrete exterior walls and curtain wall buildings. In particular, as the envelope insulation performance is improved, the proportion of thermal loss through the thermal bridge will increase [9]. Thus, the thermal bridge should be considered as the required level if thermal transmittance is increased.

The present study developed a truss insulation frame (TIF) whose sides were supported by truss-form steel wires, and the interior was filled with insulation materials to minimize the heat loss in the metal vertical members, which were major thermal bridge portions in the dry exterior insulation system. This study also evaluated the air leakage and water penetration performance of the dry exterior insulation system using the TIF, structural performance, fire resistance performance, insulation performance, condensation resistance performance, and energy performance. By doing this, an envelope system is proposed to save energy in buildings in a practical manner, and the need to strengthen the envelope insulation performance in buildings is addressed by evaluating the applicability of dry exterior insulation systems using TIF on construction sites.

1.2. Methods and Procedures

A full scale of specimens, including the TIF, was manufactured, and step-by-step envelope performance tests were conducted to analyze the overall envelope performance of dry exterior insulation systems using TIF. In addition, a building energy analysis was performed to determine the linear thermal transmittance in the thermal bridge portions of the vertical members, and to evaluate the effect of the dry exterior insulation system using the TIF on the building's energy. The study methodology and procedure were as follows:

A 4-m-wide and 8-m-high specimen was manufactured, and curtain wall mock-up tests were conducted to evaluate the air leakage and water penetration and structural performances according to the related standards of the American Society for Testing and Materials (ASTM) [10–12] and the

American Architectural Manufacturers Association (AAMA) [13,14]. An evaluation was also conducted to determine whether the design standards were met.

A 3-m-wide and 3-m-high specimen was manufactured to evaluate the thermal insulation and fire integrity to evaluate the fire resistance performance according to the fire resistance test methods [15] of Korea Standard (KS) F 2257 construction members.

A 2-m-wide and 2-m-high specimen was manufactured, and thermal transmittance and condensation resistance performance tests were conducted to evaluate the insulation performance and condensation resistance performance according to the insulation performance measurement methods [16] of KS F 2278 building components and the condensation resistance performance test methods [17] of KS F 2295 windows. In addition, to use square-shaped pipes, thermal transmittance tests were conducted under the same conditions to compare the insulation performance.

To evaluate the energy performance, a target building was chosen, and the linear thermal transmittances around the vertical members when using a square pipe and TIF were calculated. Based on the results, the required annual cooling and heating energy were calculated. For the analysis tool to evaluate the building energy performance, the passive house planning package (PHPP) was used.

2. Development of Dry Exterior Insulation System Using TIF

TIF was developed to block the heat transfer path that is formed through vertical members in the dry exterior insulation system. The galvanized steel sheets and stainless-steel wires were processed, as shown in Figure 1, to form a truss-shaped frame, and the core was filled with insulation materials.

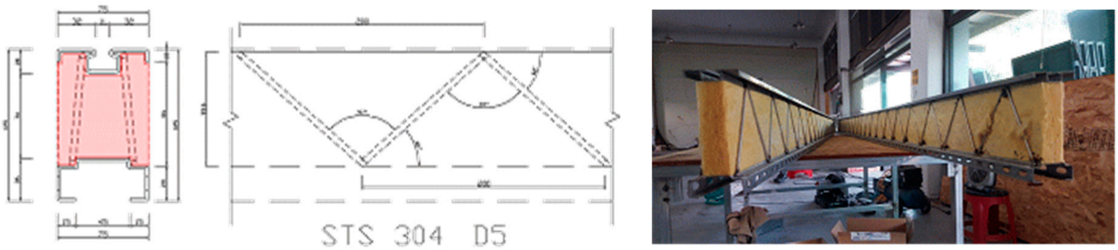


Figure 1. Truss insulation frame (TIF).

Grooves for bolting were carved in the frame to simplify the attachment of brackets and anchor bolts during the fixing to building structures in the early prototype [18].

In addition, inorganic insulation materials were used as the core material to verify the fire-protecting performance. Figure 1 shows the shape of the steel wire before inserting the insulation material into both sides of the core. Because both core insulation materials are filled during construction, the steel wires are not revealed. The TIF could replace general steel square pipes or C channels, and it can, therefore, be applied to both concrete wall-type and curtain wall-type buildings.

The dry exterior insulation system that was manufactured to conduct the envelope performance evaluation in this study employed 125 mm × 75 mm TIF as the vertical member, as shown in Figure 2, and the glass wool, which was a nonflammable insulation material, was applied, considering the fire safety and thermal conductivity for wall insulation materials. For the glass wool, a water-repellent-coated product was selected to prevent moisture absorption, and a 220-mm-thick coat was applied to satisfy 0.15 W/m^2·K, which is the current required level of the thermal transmittance in apartments located in the Central I Region of Korea.

Each of the TIFs was fixed at a distance of 1 m from the slab, and a 50 × 50 mm square pipe, which was used as the exterior material construction in the front and L-shaped transverse reinforcement for the construction of insulation material in the rear side, was fastened with brackets and screws, respectively. The L-shaped transverse reinforcement beam was a member that was directly connected to the TIF, which could be another thermal bridge. Thus, as shown in the enlarged drawing in Figure 2, it was capped with a T-shaped insulation cap made of polyamide, thus preventing additional thermal loss through the L-shaped transverse reinforcement. In addition, a membrane-like permeable waterproof sheet, which could prevent the moisture inflow from the outside while releasing the inside water vapor, was applied to the front of the insulation material, and a moisture-resisting sheet was applied to the rear side. The construction order is shown in Figure 3.

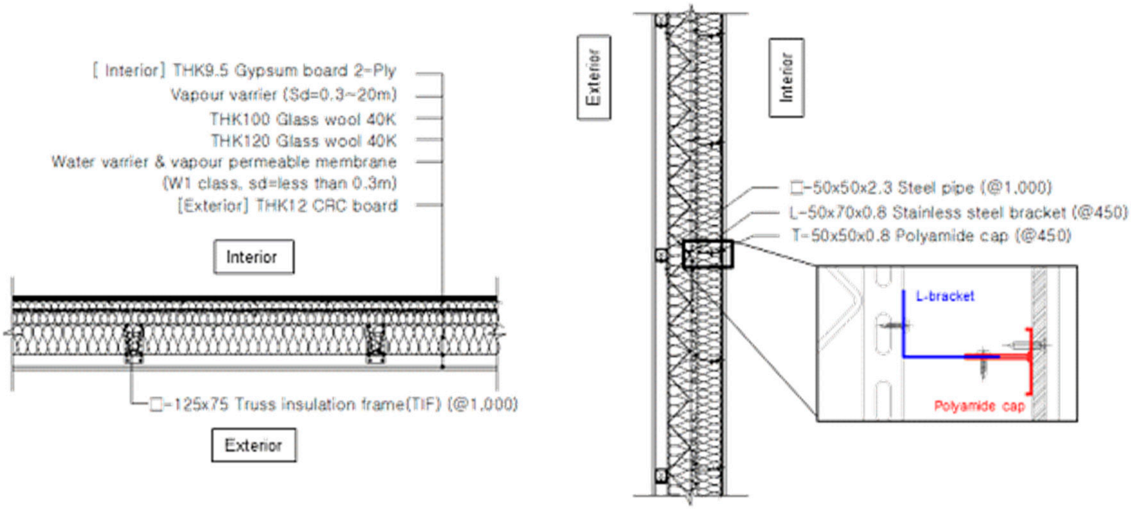


Figure 2. Configuration of the dry exterior insulation system using TIFs.

(**a**) brackets (**b**) TIFs (**c**) windows (**d**) Z-bar

(**e**) Two-ply Glass Wool (**f**) T-caps (**g**) Fixing steel pipes for exterior materials

Figure 3. Construction of the TIF exterior insulation system on the curtain wall building.

3. Performance Test Results

The envelope of buildings should be such that air leakage, water penetration, and structural performances are compliant with the fire resistance and insulation performance regulations that are set in related laws. Accordingly, the performances are shown in Figure 4, and as shown in Figure 5, full-scale tests were conducted four times to evaluate each of the performances shown in Figure 4.

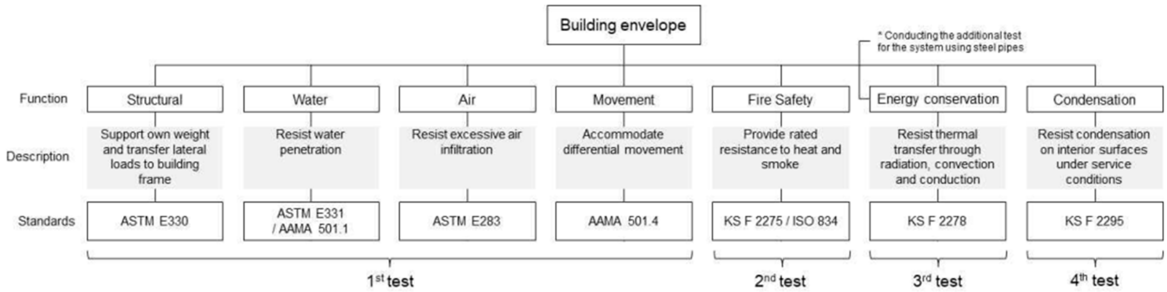
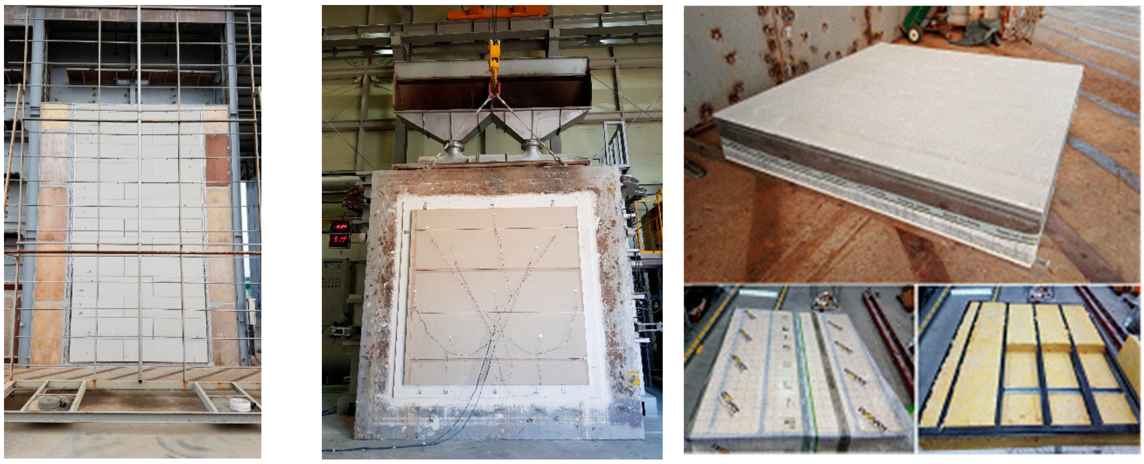


Figure 4. Test procedures of the building envelope performance.



(**a**) 1st test (Full mock-up) (**b**) 2nd test (Fire-resistance) (**c**) 3rd and 4th tests (U-value, etc.)

Figure 5. Test specimens.

The first test was a curtain wall mock-up test, in which a 4-m-wide and 8-m-high specimen was manufactured to evaluate the structural, water penetration, and air leakage performance, as well as the inter-story displacement of the system. The second test was to evaluate the thermal insulation and fire integrity of the system by manufacturing a 3-m-wide and 3-m-high specimen. The third and fourth tests were, respectively, conducted to determine the thermal transmittance and condensation prevention performance after fabricating a 2-m-wide and 2-m-high specimen. Each of the specimens had the same configuration as shown in Figure 2.

3.1. Structural Performance

For the design wind pressure for the structural performance test, the design wind pressure applied to exterior materials was calculated and applied. The positive and negative pressures that were applied were 1458 Pa and 1210 Pa based on the ground surface illumination in regions where 50-m-high medium-rise buildings were distributed in Seoul with a normal wind velocity of 26 m/s. The test standards and allowable values, as well as test results for each test, are presented in Table 1.

The structural performance was evaluated by determining whether the allowable value of the maximum deflection of TIF and exterior material was exceeded after maintaining the design wind pressure for 10 s. The residual displacement was evaluated by determining whether the allowable value of the residual displacement of TIF and exterior material was exceeded after maintaining +75%, +150% of the design wind pressure for 10 s. Both tests satisfied the allowable values proposed in the Building Construction Standard Specifications [19] and AAMA [20], thereby verifying the structural safety against wind load.

Table 1. Results of the curtain wall mock-up test.

			Results	Criterion	Standard for Test Method
Structural	TIF	Maximum deflection (Positive/negative)	8.01/6.90 mm	<10.28 mm (L/360)	ASTM E330-14: Standard test method for structural performance
		Residual deflection (Positive/negative)	1.22/1.12 mm	<7.40 mm (2 L/1000)	
	CRC Board	Maximum deflection (Positive/negative)	No Breakage (0.12/0.37 mm)	No Breakage	
		Residual deflection (Positive/negative)	No Breakage (0.25/0.03 mm)	No Breakage	
Air leakage			0.0031 $m^3/min{\cdot}m^2$	<0.0183 $m^3/min{\cdot}m^2$	ASTM E283-04: Standard test method for determining rate of air leakage AAMA 501-05: Test methods for Exterior Walls
Water penetration		Static pressure	No Water Leakage	No Water Leakage	ASTM E331-00: Standard test method for water penetration by uniform static air difference
		Dynamic pressure	No Water Leakage	No Water Leakage	AAMA 501.1-17: Standard test method for water penetration using dynamic pressure
Movement			Satisfied (Group of Essential Facilities)	Keep on function and form of all walls	AAMA 501.4-09: Static test method subjected to seismic and wind-induced interstory drifts

The inter-story drift test evaluates whether there are any abnormalities in the functions and forms of all members after applying a displacement of 1/100 of the story height on the right and left sides to the middle slab of the specimen. A displacement of 37 mm was applied based on the application of a 3.7 m story height, and the functions of the envelope, air leakage and water penetration performance, and the structural performance were maintained at the same value as before without visible damage and falling off. This satisfies the requirements of the essential facility group, such as standard occupancy (general buildings), high-occupancy assembly (buildings of densely populated occupancy), and essential facility (important buildings such as hospitals, schools, fire stations, etc.).

3.2. Air Leakage and Water Penetration Performance

The air leakage performance measures the amount of air leakage through the specimen after the standard pressure difference (+75 Pa) is maintained in the specimen, and it evaluates whether the allowable value is satisfied after the leakage measurement is converted to one at a standard state. The test result showed that the air leakage through the specimen was 0.031 $m^3/(min{\cdot}m^2)$ at 75 Pa. This was around 1/6 of the level of 0.183 $m^3/(min{\cdot}m^2)$ at 75 Pa, which is the allowable leakage rate for general buildings recommended by the AAMA 501 [21], and satisfied the recommended standard. (In AAMA 501, the air leakage performance criteria are recommended by classifying buildings into two groups: General buildings and buildings whose air quality and humidity control are important). AAMA 501 is cited as the criteria for curtain wall-fixed portions during mock-up tests of curtain walls in Korea: General buildings: 0.06 cfm/ft^2 (=0.183 $m^3/(min{\cdot}m^2)$) or smaller (based on a pressure difference of 75 Pa), and buildings whose air quality and humidity control are important: 0.06 cfm/ft^2 or smaller (based on a pressure difference of 300 Pa).

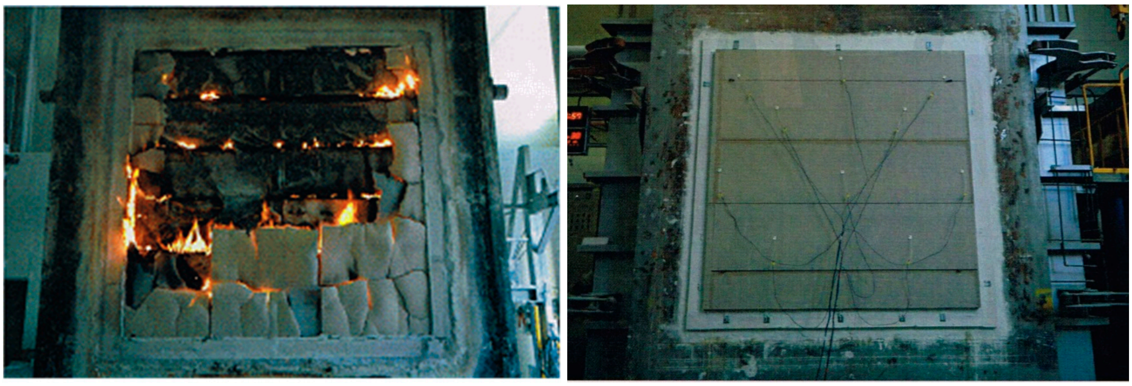
The water penetration performance was conducted by spraying water at a rate of 204 L/m^3 per hour for 15 min, while maintaining a minimum pressure (+300 Pa) or blowing externally wind that corresponded to the minimum pressure (dynamic pressure condition) proposed by AAMA 501 (static pressure condition). It also involved determining whether water leakage occurred in the specimen, and both tests satisfied the water penetration performance criteria without leakage.

3.3. Fire Resistance Performance

The fire resistance performance of the envelope was measured by exposing the two sides of the specimen, including the exterior and interior materials, to a heating furnace (exposed side) and outside air (unexposed side). In addition, the temperature inside the heating furnace was heated according to the standard heating curve, thereby enabling the evaluation of the thermal insulation, which limited the temperature rise level at the unexposed side of the specimen below the specified level, and the fire integrity that prevented passing flame or high-temperature gases or flame occurrence at the unexposed side. The thermal insulation and fire integrity test results are shown in Table 2 and Figure 6, respectively.

Table 2. Results of the fire resistance test.

Performance Criteria		Time	Results	Criterion	Reference
Thermal insulation	Average increased temperature	30 min	0.9 K	<140 K	KS F 2275 ISO 834
	Maximum increased temperature		1.8 K	<180 K	
Fire integrity	Cracks gaps of 6 mm		n/a	should not	
	Cracks gaps of 25 mm		n/a	should not	
	Sustained flaming on the unexposed side		n/a	should not	
	Ignition of a cotton wool pad		n/a	should not	



(**a**) Furnace side (**b**) Outdoor air side

Figure 6. Specimen after the fire resistance test.

The thermal insulation was evaluated by the elapsed time for which the average increased temperature was maintained below 140 K and the maximum increased temperature below 180 K at the unexposed side of the specimen compared to the initial temperature. The fire integrity was evaluated by considering the elapsed time from the penetration through the crack gauge, flame occurrence at the unexposed side, and to the ignition of the cotton wool pad. For the dry exterior insulation system using TIF, its average and maximum increased temperatures after 30 min heat up were 0.9 K and 1.8 K, respectively, which satisfied both thermal insulation and fire integrity for 30 min. Thus, it satisfied the nonbearing exterior wall criteria [22] among the fireproof construction performance criteria.

3.4. Insulation Performance

The specimens were installed in the middle of the constant-temperature and low-temperature rooms according to the guarded hot box of KS F 2277, and calories supplied to maintain the temperature in the constant-temperature room were measured to evaluate the thermal transmittance of the component. For the insulation performance, specimens that had the same insulation structure and size were fabricated, even when using the square pipe to perform the thermal transmittance test.

The insulation material was constructed in the two layers, which was the same as the use of the TIF, and the insulation material was continuous in the rear side of the square pipes, except for measurement points that connected vertical and horizontal members (points indicated in Figure 7).

Figure 7. Test specimen for the dry exterior insulation system using steel pipes.

Table 3 presents the test results of the thermal transmittance. The calculated one-dimensional (1-D) thermal transmittance value that did not consider a two-dimensional (2-D) and three-dimensional (3-D) thermal bridge, such as vertical and horizontal members, was 0.145 W/(m^2·K) and, when considering the dry exterior insulation system using square pipes, the thermal transmittance was 0.19 W/(m^2·K), which increased by 31% compared to the calculated 1-D thermal transmittance value. This result indicated that an additional thermal loss occurred owing to the connected points with square pipes and horizontal members, even if the insulation materials were continuous on the rear side of the square pipes. In contrast, the thermal transmittance of the dry exterior insulation system using TIF was 0.15 W/(m^2·K), and increased by 3.4%, indicating that the insulation performance closer to the calculated 1-D thermal transmittance value could be ensured.

Table 3. Test results of U-value.

	Steel Pipe	**TIF**
Specimen	THK9.5 × 2 Gypsum -THK100 G/W (40 K) -THK120 G/W (40 K) -THK50 Cavity (R = 0.086(m^2·K)/W) -THK12 CRC board	THK9.5 × 2 Gypsum -Vapor barrier -THK100 G/W (40 K) -THK120 G/W (40 K) -Water barrier -THK50 Cavity (R = 0.086 (m^2·K)/W) -THK12 CRC board
U-value (1D)	0.145 W/(m^2·K)	0.145 W/(m^2·K)
U-value	0.19 W/(m^2·K)	0.15 W/(m^2·K)
Increasing ratio	+0.045 (+31.0%)	+0.005 (+3.4%)

3.5. Condensation Prevention Performance

The condensation prevention performance of the envelope was evaluated by observing a surface temperature in the indoor side after installing a specimen in the middle of the constant- and low-temperature rooms according to KS F 2295. Here, the temperature conditions of the rooms were 25 °C for the constant-temperature room (T_{hot}) and −15 °C for the low-temperature room (T_{cold}) by referring to the design criteria for condensation prevention in apartments [23]. The same specimen configuration was set up with that of the thermal transmittance test, and the measurement points of the surface temperature on the indoor side are shown in

The test results of the condensation prevention performance showed that the surface temperature at 25 points was 24.2 °C on average, 24.6 °C at maximum, and 23.0 °C at minimum, as shown in Table 4, and the values decreased by less than 2 °C compared to those in the constant-temperature room. In particular, with the exception of measurement points No. 21 and No. 22, all measurement points showed a temperature difference of around 1.0 °C in comparison to the constant-temperature room. Further, no effective difference was found in the surface temperature according to the measured portions, such as the rear sides of the vertical and horizontal members. Figure 8.

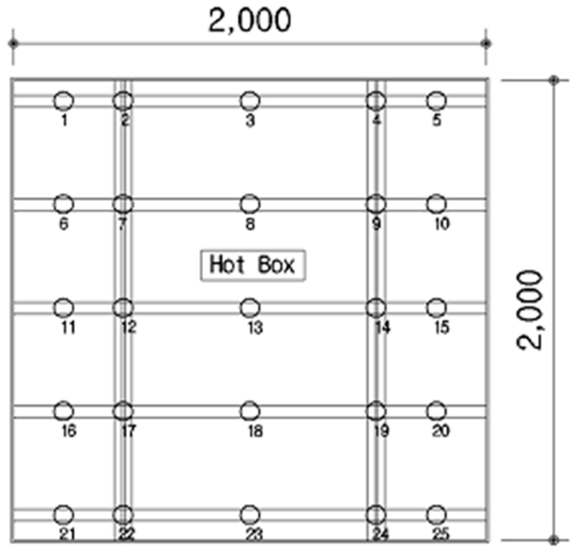


Figure 8. Measurement points for condensation risk.

Table 4. Test results of condensation risk (Unit: °C).

No.	**1**	**2**	**3**	**4**	**5**
T_m	24.1	24.1	23.9	24.4	24.5
$T_{int.} - T_m$	0.9	0.9	1.1	0.6	0.5
TDR	0.02	0.02	0.03	0.02	0.01
No.	6	7	8	9	10
T_m	24.2	24.1	24.4	24.4	24.6
$T_{int.} - T_m$	0.8	0.9	0.6	0.6	0.4
TDR	0.02	0.02	0.02	0.01	0.01
No.	11	12	13	14	15
T_m	24.4	23.9	24.2	24.2	24.4
$T_{int.} - T_m$	0.6	1.1	0.8	0.8	0.6
TDR	0.01	0.03	0.02	0.02	0.01
No.	16	17	18	19	20
T_m	24.2	24.2	24.4	24.5	24.3
$T_{int.} - T_m$	0.8	0.8	0.6	0.5	0.7
TDR	0.02	0.02	0.02	0.01	0.02
No.	21	22	23	24	25
T_m	23.0	23.5	24.4	24.4	24.6
$T_{int.} - T_m$	2.0	1.5	0.6	0.6	0.4
TDR	0.05	0.04	0.01	0.02	0.01
Total	-	Average	Max.	Min.	SD
	T_m	24.2	24.6	23.0	0.34
	$T_{int.} - T_m$	0.8	0.4	2.0	0.34
	TDR	0.02	0.05	0.01	0.009

Where, $TDR = (T_{int.} - T_m)/(T_{int.} - T_{ext.})$, $T_{int.}$ = 25 °C, $T_{ext.}$ = −15 °C, T_m = measured temperature.

4. Evaluation of Building Energy Performance

Previously, several studies were conducted to determine the effect of the heat loss through the thermal bridge of a building envelope on heating and cooling loads in buildings. Song et al. [24] calculated the linear thermal transmittance in major structural joints during interior and exterior insulation construction and compared annual cooling and heating loads to determine the above results.

Lee et al. [25] calculated the linear thermal transmittance in major structural joints when applying exterior insulation precast concrete (PC) walls for calculating the heating load in a building.

In the present study, the annual cooling and heating demand in the building was determined by finding the linear thermal transmittance in the vertical member areas during the construction of dry exterior insulation system. Then, a comparison was made of the results and those obtained by the use of the square pipe with the use of TIF, thus aiming to evaluate quantitatively the energy performance of the dry exterior insulation system using TIF.

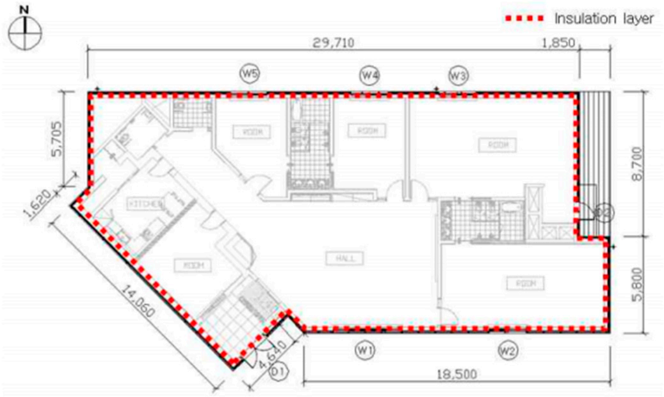
4.1. Evaluation Overview

For the analysis tool to evaluate the building energy performance, the PHPP in Germany was used. The PHPP is a building energy analysis tool using spreadsheets. It is based on the monthly calculation method proposed by ISO 13790 [26]. The monthly calculation method calculates the number of calories, that is, the cooling and heating energy demand, required to maintain heating and cooling set temperatures for monthly average outdoor air temperatures considering the heat loss due to envelopes, ventilation, and heat gain resulting from internal heating and solar radiation in a building. Assuming that there is a continuous heating and cooling operation, this study applied heat gain and heat loss calorie utilization coefficients when calculating the heating and cooling energy demands in order to determine the heat capacity of building elements that were in direct contact with indoor air [24].

The building selected to analyze the building energy is shown in Figure 9. It was a one-story childcare building located in Seoul, and the interior spaces of the insulation material construction line were all assumed to be a heating space. The thermal transmittance of the exterior wall was assumed to be at the same level as that of the mock-up specimen. Accordingly, the thermal transmittance of the window was set to the level of a passive house (refer to Table 5). By referring to the climate data of the Seoul area, the monthly average outdoor air temperature and solar radiation by direction were substituted and set temperatures of 20 °C and 25 °C were assumed for heating and cooling, respectively. It was assumed that the number of occupants was 15, and that the internal caloric value, of 4.10 W/m^2, was applied in the childcare facility in the PHPP. Because no additional criteria about the number of indoor ventilations in the childcare were available, this study assumed 0.5 time/h, along with the use of a heat-recovery ventilation system.

Table 5. U-values of the envelope.

	Materials	U-Value
Exterior Wall (Curtain wall)	(Exterior) THK30 Stone -THKVar. Cavity (R = 0.086 (m^2·K)/W) -THK220 G/W -THKVar. Cavity (R = 0.086 (m^2·K)/W) -THK9.5 Gypsum board (Interior)	0.145 W/(m^2·K)
Roof	(Exterior) THK100 Plain concrete -Waterproofing membrane -THK150 Concrete -THK185 XPS -THK9.5 Gypsum board (Interior)	0.143 W/(m^2·K)
Floor	(Interior) THK50 Heating panel -THK130 Rigid PU foam board -THK30 EPS -THK150 Concrete (Exterior)	0.145 W/(m^2·K)
Fenestration	Window: 0.878 W/(m^2·K), Door: 1.392 W/(m^2·K)	



Plan

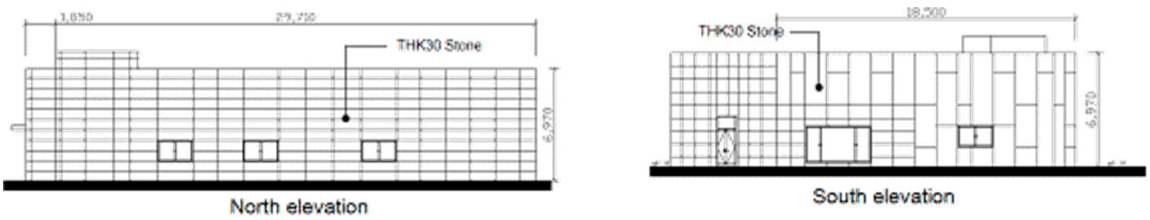


Figure 9. Plan and elevation of the example building.

4.2. Calculation of Linear Thermal Transmittance

To determine the effect of the vertical member in the dry exterior insulation system, the linear thermal transmittance of the thermal bridge portion in the vertical member was calculated, which was then reflected in the calculation of cooling and heating energy demand in buildings. In the monthly calculation method, the linear thermal transmittance (Ψ_j) in the thermal bridge portion and corresponding thermal bridge length (l_j) were inputted and reflected in Equation (1) in the calculation of envelope heat loss.

$$Q_{tr} = \left(\sum_i U_i A_i + \sum_j \Psi_j l_j \right) \times f_t \times (\theta_{int.set} - \theta_{ext.mn}) \times t \quad (1)$$

where

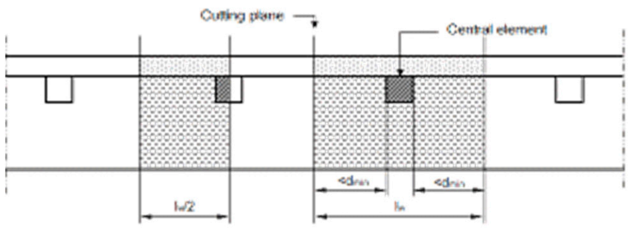
Q_{tr}: Envelope heat quantity (MJ),
U_i: Thermal transmittance of general portion i (W/(m^2·K)),
A_i: Area of corresponding portion (m^2),
Ψ_j: Linear thermal transmittance of thermal bridge portion j (W/(m·K)),
l_j: Length of the corresponding thermal bridge portion (m),
f_t: Temperature coefficient factor (directly facing the outdoor air: 1.0),
$\theta_{int.set}$: Indoor set temperature in heating or cooling mode (°C),
$\theta_{ext.mn}$: Monthly average outdoor air temperature (°C), and
t: Calculation time interval (Ms).

The linear thermal transmittance can be calculated using Equation (2), and the evaluation portion to calculate the heat quantity per unit length was set by referring to ISO 10211 [27]. This standard proposes that if the distance to the symmetry plane is 1 m or smaller than three times the structure thickness in the general portion, the evaluation portion is to be set up at the symmetry plane for repeated thermal bridge portions, as shown in Figure 10a. This can be used to determine the vertical member of the dry exterior insulation system constructed at a constant distance. To include the effect of the stainless-steel wire of the TIF, a 3-D shape whose unit height was 1.0 m was set to the final evaluation model (refer to Figure 10b). In the case where square pipes were used as the vertical member, a case was set depending on whether the insulation material at the rear side of the square pipe had been constructed.

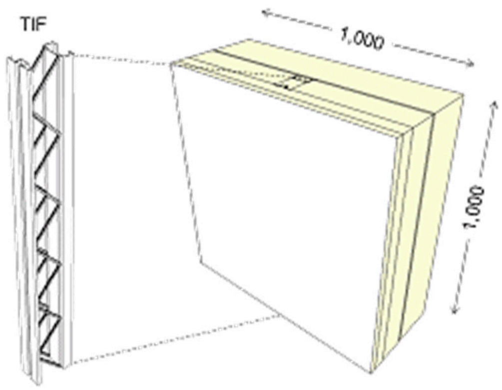
$$\Psi = \frac{\Phi}{\Delta T} - \sum U_i l_i \tag{2}$$

where

Ψ: Linear thermal conductivity (W/(m·K)),
Φ: Heat quantity per unit length of the evaluation portion (W/m),
ΔT: Temperature difference between indoor and outdoor (K),
U_i: Thermal transmittance in the general portion (flanking elements) (W/(m^2·K)), and
l_i: Length of general portion (flanking elements) (m).



(**a**) 3-D model in TRISCO for the TIF



(**b**) ISO 10211 cutting planes of linear thermal bridges at fixed distances

Figure 10. The 3-D model according to ISO 10211.

Physibel TRISCO 14.0w [28] was used for the heat quantity analysis program for the calculation of the linear thermal transmittance, and the boundary conditions between indoor and outdoor and material properties are presented in Table 6. In the analysis, the cavity layer inside the evaluation model was assumed to be a solid that had an equivalent thermal conductivity. For the continuous cavity layer with a large width and height, and which was formed between a stone exterior and insulation material, and between insulation material and gypsum board, the equivalent thermal conductivity was also calculated and inputted, as presented in Equation (3). This satisfied the energy-saving design criteria (Table 6) of the thermal resistance 0.086 (m^2·K)/W building that was applied during the calculation of the 1-D thermal transmittance in the general portion (flanking elements) and a 1.0 cm or thicker air layer constructed in sites [3]. For the cavity layer inside the square pipes and TIF, an equivalent thermal conductivity that was automatically calculated by the program was used to increase the accuracy of the analysis.

$$\lambda_{eq} = \frac{d_{cavity}}{R_{cavity}} \tag{3}$$

where

λ_{eq}: Equivalent thermal conductivity in the cavity layer (W/(m·K)),
d_{cavity}: Design thermal resistance in the cavity layer ((m^2·K)/W), and
R_{cavity}: Thickness of the cavity layer (m).

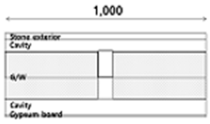
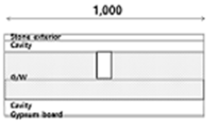
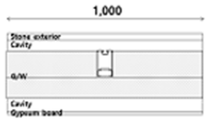
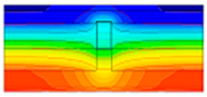
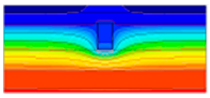
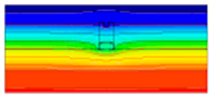
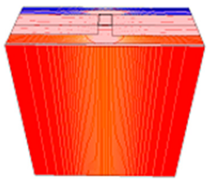
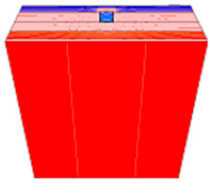
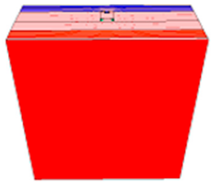
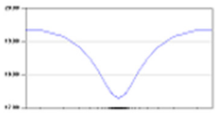
Table 6. Boundary conditions and material properties.

	Temperature (°C)	**Surface Heat Transmittance (W/(m^2·K))**	
Outdoor	−11.3	23.25	
Indoor	20.0	9.09	
Materials	**Thermal Conductivity (W/(m·K))**	**Materials**	**Thermal Conductivity (W/(mK))**
Concrete	1.6	Gypsum board	0.18
Steel	53.0	Stone exterior	3.3
Stainless steel	15.0	Glass-wool (G/W)	0.034

The length of the thermal bridge was calculated by determining the width of the elevation by direction, the distance between vertical members, and the story height. Although there was a slight difference owing to the location of the door and windows, the construction distance between vertical members averaged 1.0 m, and the height of the story was assumed to be up to 3.5 m for the length of the thermal bridge in the vertical member that affected the building energy. Table 7 presents the calculation results of the thermal transmittance.

The lowest surface temperature on the indoor side of Type A, which has no insulation on the rear side of the square pipe, was 17.3 °C and the linear thermal transmittance was 0.241 W/(m·K). The lowest surface temperature on the indoor side of Type B, which took an insulation measure on the rear side of the square pipe, was 19.3 °C and the linear thermal transmittance was 0.027 W/(m·K). In contrast, for Type C, which replaced the square pipe with TIF, its linear thermal transmittance was reduced to 0.010 W/(m·K) and the lowest surface temperature on the indoor side was 19.4 °C. The lowest internal surface temperature was found on the rear side of the vertical member, but the difference between the highest and lowest surface temperatures was 0.07 °C, indicating that the deviation in the surface temperature on the indoor side according to the location of the vertical member was minimal. For Types A and B, the differences between the highest and lowest temperatures were 2.09 °C and 0.17 °C, respectively; the reduction in the surface temperature on the rear side of the vertical member was clearly seen in Type A, while it was insignificant in Type B.

Table 7. Calculated linear thermal transmittance values.

		(A-type) Steel Pipe without the Additional Insulation	**(B-type) Steel Pipe with the Additional Insulation**	**(C-type) TIF**
Images	Model			
	Isothermal (2D) (Increment = 1.0 °C)			
	Isothermal (3D) (Increment = 0.1 °C)			
	Temperature profile X-axis: grids Y-axis: Temperature Range (17–20 °C)			
Indoor lowest surface temperature (Indoor air temperature 20 °C)		17.3 °C	19.3 °C	19.4 °C
Linear thermal transmittance, Ψ_i		0.234 W/(m·K)	0.027 W/(m·K)	0.010 W/(m·K)
Total length of linear thermal bridges, l_i			251.8 m	

4.3. Analysis of the Reduction Effect of Annual Cooling and Heating Energy Demand

The calculation results of the annual cooling and heating energy demand using the PHPP are presented in Table 8. To estimate the overall effect of the thermal bridge on the vertical member, the cooling and heating energy demand was calculated in Case 1 without determining the linear thermal transmittance. In Case 1, the annual heating and cooling energy demands were 15.68 kWh/m^2 and 9.53 kWh/m^2, respectively.

In Table 8, Cases 2 to 4 show the results of the linear thermal transmittance of the thermal bridge in Types A, B, and C in Table 7. The annual heating energy demands of Cases 2 to 4 were 25.42, 16.78, and 16.09 kWh/m^2, which increased by 62.1, 7.0, and 2.6%, respectively, compared to that of Case 1. For Case 2, for which there was no insulation measure on the rear side of the square pipe, the increased rate of heat loss relative to that of Case 1 was more than 60%, which indicated that measures should be taken to reduce the heat loss in the corresponding thermal bridge portion in order to decrease the actual heating energy. For Case 3, for which there was a measure of insulation on the rear side of the square pipe, the rate and amount of increase were 7.0% and 1.10 kWh/m^2, respectively, which were significantly reduced compared to those of Case 2. For the case that involved replacing the square pipe with TIF, the rate and amount of increase were 2.6% and 0.41 kWh/m^2, respectively, which indicated that the heating energy demand was the lowest.

Table 8. Annual heating and cooling energy demands.

Month	Case 1 (Without Thermal Bridges)		Case 2: A-Type (Steel Pipe Without the Additional Insulation)		Case 3: B-Type (Steel Pipe with the Additional Insulation)		Case 4: C-Type (TIF)	
	Heating (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)	Cooling (kWh/m^2)	Heating (kWh/m^2)	Cooling (kWh/m^2)
1	5.00	0.00	7.45	0.00	5.28	0.00	5.11	0.00
2	3.55	0.00	5.49	0.00	3.77	0.00	3.63	0.00
3	2.00	0.00	3.56	0.00	2.18	0.00	2.07	0.00
4	0.02	0.00	0.30	0.00	0.03	0.00	0.02	0.00
5	0.00	0.02	0.00	0.01	0.00	0.02	0.00	0.02
6	0.00	1.67	0.00	1.38	0.00	1.63	0.00	1.66
7	0.00	2.98	0.00	2.98	0.00	2.98	0.00	2.98
8	0.00	3.32	0.00	3.35	0.00	3.32	0.00	3.32
9	0.00	1.53	0.00	1.15	0.00	1.49	0.00	1.52
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	1.17	0.00	2.53	0.00	1.32	0.00	1.23	0.00
12	3.94	0.00	6.10	0.00	4.19	0.00	4.04	0.00
Total	15.68 (-)	9.53 (-)	25.42 (+62.1%)	8.87 (-6.9%)	16.78 (+7.0%)	9.45 (-0.8%)	16.09 (+2.6%)	9.50 (-0.3%)
	25.21 (-)		34.29 (+36.0%)		26.24 (+4.1%)		25.59 (+1.5%)	

The cooling energy demands in Cases 2 to 4 were 8.87, 9.45, and 9.50 kWh/m^2, which showed an opposite trend to those of the heating energy demand, which was due to the increase in the quantity of lost calories utilized effectively during cooling. The reduction in the cooling energy demand was around 7% of the increase in the heating energy demand. The total cooling and heating energy demands were 25.21, 34.29, 26.24, and 25.59 kWh/m^2 in Cases 1, 2, 3, and 4, respectively, and the total rate of increase for Case 2 compared to Case 1 was 36.0%, while those of Cases 3 and 4 were, respectively, 4.1% and 1.5% compared to that of Case 1.

Figure 11 shows the percentage of heat loss in the thermal bridge portion of the vertical member for each case compared to the envelope's heat loss amount. Of the total heat loss, the percentages of heat loss in the thermal bridge portion were 25.7, 3.8, and 1.5% in Cases 2, 3, and 4, respectively. Without the insulation measures on the rear side of the square pipe, the proportion of the heat loss relative to the total heat loss was 25.7%, which was the highest in all elements in Case 2. Meanwhile, the proportion of the heat loss through walls, including the thermal bridge, was close to 50% in Case 2. With the insulation measure on the rear side of the square pipe, the proportion was reduced to 3.8% and, with the use of TIF, the proportion decreased to 1.5% of the total heat loss.

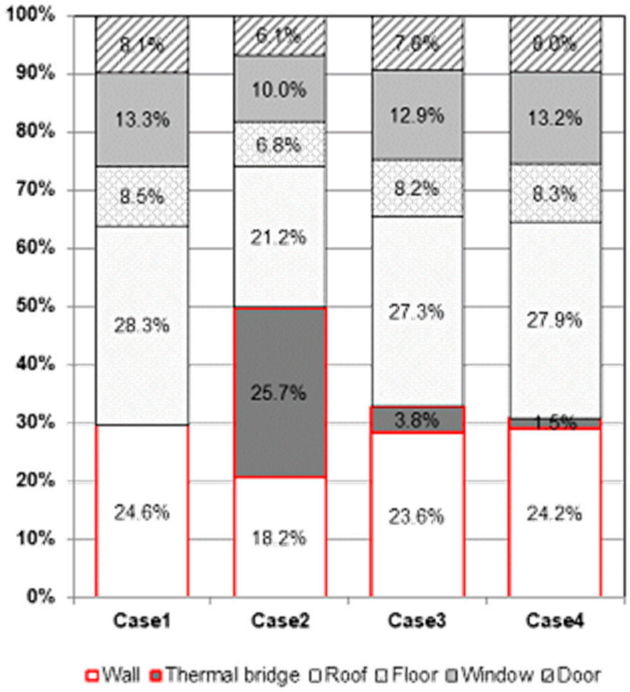


Figure 11. Percentage of heat lost through thermal bridges.

5. Conclusions

This study evaluated the site applicability of the dry exterior insulation system by conducting a performance evaluation of the overall envelope using TIF. The TIF was developed to minimize the heat loss through metal vertical members, which were major thermal bridge portions in the dry exterior insulation system. The main results of the study are as follows:

(1) For the overall envelope performance evaluation, the structural performance, air leakage, water penetration performance, insulation performance, and condensation prevention performance were determined. The structural performance test results showed that both the allowable values of the maximum and residual deflections were robust to the design wind pressure, and the inter-story drift test results also indicated that no problems occurred in the forms and functions, verifying the robustness to wind and seismic loads. The air leakage and water penetration performance test results also satisfied the allowable air leakage rate, and no additional water leakage occurred. The fire resistance test results also verified that there was thermal insulation and fire integrity for 30 min, satisfying the fire resistance structure approval criteria of nonbearing walls.

(2) The insulation performance test results showed that when using the TIF, the thermal transmittance was 0.15 W/(m^2·K), which was an increase of 3.4% compared to the calculated value of 1-D thermal transmittance without considering the thermal bridge. Further, the results verified that the heat loss was significantly reduced at the thermal bridge portion compared to a thermal transmittance of 0.19 W/(m^2·K) when using the square pipe.

(3) The condensation prevention performance test results showed that the difference between the surface temperature on the indoor side and the air temperature in the constant-temperature room was within 2.0 °C, indicating that condensation was unlikely to occur.

(4) The annual heating energy demand of the target building was calculated to determine the linear thermal transmittance in the thermal bridge portion, and the results showed that, when using the TIF, the thermal transmittance was 16.09 kWh/m^2, a reduction of 36.7% compared to 25.42 kWh/m^2, which was the annual heating energy demand of the dry exterior insulation system without

the additional insulation measure. Further, it was reduced by 4.1% compared to 16.78 kWh/m^2, which was taken with the insulation measure.

(5) The proportion of heat loss in the vertical member compared to the heat quantity loss in the envelope was 25.7% in the case involving the use of the square pipe without the insulation measure in the rear side, which was very high. The proportion was 3.8% with the insulation measure on the rear side of the square pipe, and 1.5% when using the TIF, which showed a decreasing trend.

(6) In conclusion, when using the TIF by replacing existing square pipes or C channels, the effects of a significant reduction in thermal bridge through the corresponding portion, as well as a reduction in the heating energy demand, are expected.

For future studies, the construction performance and economic feasibility of the dry exterior insulation system using TIF will be analyzed through a number of site applications.

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Nomenclature

$T_{int.}$	Indoor temperature [°C]
$T_{ext.}$	Outdoor temperature [°C]
T_m	Measured temperature on indoor surface [°C]
Q_{tr}	Envelope heat quantity [MJ]
U_i	Thermal transmittance of general portion i [W/(m^2·K)]
A_i	Area of corresponding portion i [m^2]
Ψ_j	Linear thermal transmittance of thermal bridge portion j [W/(m·K)]
l_j	Length of the corresponding thermal bridge portion j [m]
f_t	Temperature coefficient factor (directly facing the outdoor air: 1.0)
$\theta_{int,set}$	Indoor set temperature in heating or cooling mode [°C]
$\theta_{e,mn}$	Monthly average outdoor air temperature [°C]
t	Calculation time interval [Ms]
Ψ	Linear thermal transmittance [W/(m·K)]
Φ	Heat quantity per unit length of the evaluation portion [W/m]
ΔT	Temperature difference between indoor and outdoor [K]
U_i	Thermal transmittance in the general portion [W/(m^2·K)]
l_i	Length of general portion [m]
λ_{eq}	Equivalent thermal transmittance in the cavity layer [W/(mK)]
R_{cavity}	Design thermal resistance in the cavity layer [(m^2·K)/W]
D_{cavity}	Thickness of the cavity layer [m]
TIF	Truss insulation frame
PHPP	Passive house planning package
cfm	Cubic feet / minute
CRC board	Cellulose fiber reinforced cement board
THK	Thickness
TDR	Temperature difference ratio
ISO	International Standard Organization
MJ	Mega Joule (10^6)
Ms	Minutes
G/W	Glass wool
XPS	Extruded polystyrene sheet
PU	Polyurethane
EPS	Expanded polystyrene sheet

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