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Investigation of Thermal and Energy Performance of the Thermal Bridge Breaker for Reinforced Concrete Residential Buildings

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Abstract: Thermal bridges in building envelopes can cause significant heat loss and heat gain. In this study, the developed thermal bridge breaker was applied to an interior insulation finishing system in residential buildings to minimize the thermal bridges in building envelopes. To investigate the thermal and energy performance of the developed thermal bridge breaker, the surface temperatures and heat flow at the wall and floor junctions were predicted using Physibel. In addition, the heating and cooling energy consumption in a residential building was analyzed by EnergyPlus. As a result, the use of the thermal bridge breaker can minimize the effective thermal transmittance in the building envelope system. Moreover, when the building envelopes were equipped with the thermal bridge breaker, the heating and cooling load through the exterior walls was decreased by 15–27%. Thus, the thermal bridge breaker can play an important role in minimizing the heat loss and occurrence of condensation in building envelopes.

Keywords: thermal bridge; envelop; energy performance

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1. Introduction

Globally, one-third of the total energy consumption is consumed by buildings accompanied by the rapid increase in CO_2 emissions [1–3]. Current studies report that the energy consumed by buildings has kept increasing significantly, and in the foreseeable future, it will become of notable concern [4–7]. Dong et al. [8] observe that the energy consumption in buildings can be remarkably reduced with only a slight improvement in the building energy efficiency. Thus, it is important to find ways to improve the energy efficiency in buildings. In South Korea, the energy consumption of buildings has also become a major issue. According to the "Energy Statistics Handbook in 2020", provided by the Korea Energy Agency [9], about 20% of total energy is consumed by buildings. Among building types, nearly 40% of the total building energy consumption is consumed by residential buildings [9]. Concerning the improvement in building energy efficiency, the Korean government has developed a renewable energy policy to achieve the goal of producing 20% of total electricity by implementing green technologies by 2030 [10–12]. In 2018, "The Amendment Plan of 2030 GHG Reduction Roadmap" was also released to reduce GHG emissions by 9.6 million tons of CO_2, by improving building energy efficiency [13,14]. With regard to the reduction in building energy and GHG emissions, several policies, such as building energy efficiency and zero energy buildings, have also been developed.

To achieve the goal of net or nearly zero energy buildings, several design strategies are needed that combine passive and active design solutions, and renewable energy systems. As one of the passive design strategies, improvements in building envelopes' performance can provide the potential for reductions in energy consumption, as well as improvements in

thermal comfort for the occupants [15]. Architectural design parameters, such as window-to-wall ratios, natural ventilation, and building shapes, can also be considered as passive design solutions [15]. Moreover, the high degree of functional integration in mechanical systems, such as heating, ventilation, and air conditioning (HVAC), can provide an opportunity for active design strategies to lead to better control of thermal comfort and energy saving [16]. By offsetting building energy consumption through passive and active design strategies, the remaining energy needs should, as much as possible, be covered by renewable energy systems [17]. Among these available design solutions and technologies, the first consideration is to determine the most energy efficient measures among the passive design solutions [18].

As mentioned earlier, passive design solutions mainly include the design parameters of building envelopes and building shapes. Lin et al. [19] reviewed zero energy buildings and found that the thermal properties and airtightness of building envelopes, including walls, exterior windows, and roofs, have a significant impact on the building energy consumption and the indoor environment. Specifically, the building envelope-related technologies include a high insulation performance of the materials of building envelopes, advanced window systems, and external and internal shadings [16,20–25]. While previous studies have focused on the investigation of the thermal performance of materials and the energy efficiency of several design parameters of building envelopes, a few studies have analyzed the impact of thermal bridges in building envelopes on the energy efficiency and thermal performance of buildings [26].

In general, thermal bridges can occur due to discontinuous thermal insulation (e.g., repetitive structural members and their junctions) in the building envelope, causing significant heat loss and gain in the winter and summer, respectively [26–28]. Theodosiou and Papadopoulos [29] showed that about one-third of heating energy can be lost through thermal bridges in residential buildings, even where they were equipped with high-performance windows and highly insulated building envelope systems. To minimize these thermal bridges, several studies have been conducted to reduce the annual energy consumption in buildings by utilizing thermal bridge breaks or advanced materials in the exterior insulation finishes of building envelopes [30–34]. Insulation that was 10 to 80 mm thick and 1100 mm long was installed on both sides of the partition wall, in contact with the external wall, which was made of concrete to prevent thermal bridging [35]. In South Korea, most residential buildings have generally been constructed with an interior insulation finishing system, where the fixing components can become a major path for heat flow, causing thermal bridges between the slab and the exterior walls [36,37]. In addition, it is difficult to apply an exterior insulation finishing system to remove thermal bridges, as this can increase the construction cost, as well as require specific construction skills. Therefore, thermal breaks for interior insulation finishing systems need to be developed to minimize thermal bridges in building envelopes.

Focusing on minimizing thermal bridges in building envelopes, this study develops the thermal bridge breaker for an interior insulation finishing system, by analyzing the thermal performance of a high-rise apartment building. Specifically, the effect of thermal transmittance, by the influence of thermal bridges with the developed thermal break, on the total heat flow is estimated by Physibel. In addition, the impact of the developed thermal break, for the interior insulation finishing system, on the building energy consumption can be compared with that on the conventional building envelope system by utilizing EnergyPlus.

2. Thermal Bridge Breaker

Figure 1 shows the developed thermal bridge breaker in an interior insulation finishing system, to minimize the thermal bridge between an exterior wall and a concrete slab. Specifically, it is a complete system, where 150 mm insulation boards and 50 mm concrete (ultra-high-performance concrete, UHPC) ribbed slabs alternate. In addition, each concrete slab in the developed thermal bridge breaker is connected with a reinforcing bar, as shown

in Figure 1. One module is composed of five insulation boards and concrete slabs, and the length of a module is 1 m.

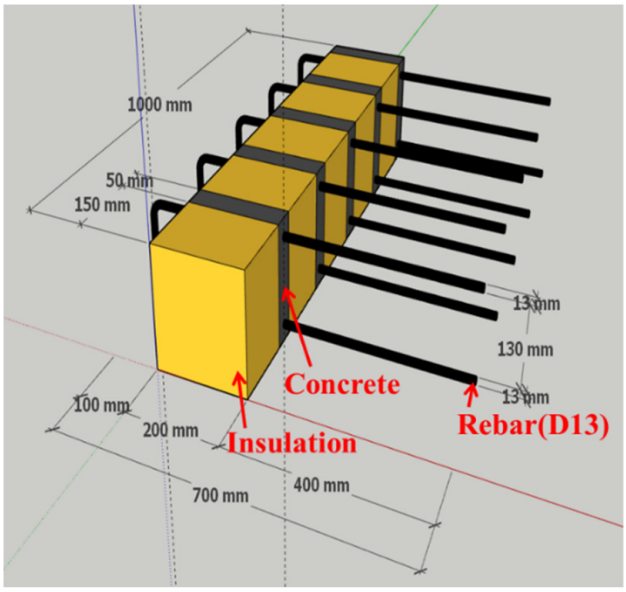


Figure 1. Thermal bridge breaker.

Figure 2 shows that the connection between the exterior wall and the concrete slab in a building is equipped with a thermal bridge breaker to test the performance of the thermal bridge breaker, where this structure is constructed based on the design guidelines for building energy efficiency provided by the Korea Energy Agency [38]. In detail, 190 mm and 30 mm insulation boards for the wall and slab were used, respectively. Additionally, the insulation board (thickness: 15 mm, depth: 450 mm) was located in the ceiling, where severe thermal bridges might occur. The use of additional insulation boards in the ceiling is generally recommended for the construction of residential buildings in South Korea, to prevent condensation by the thermal bridge.

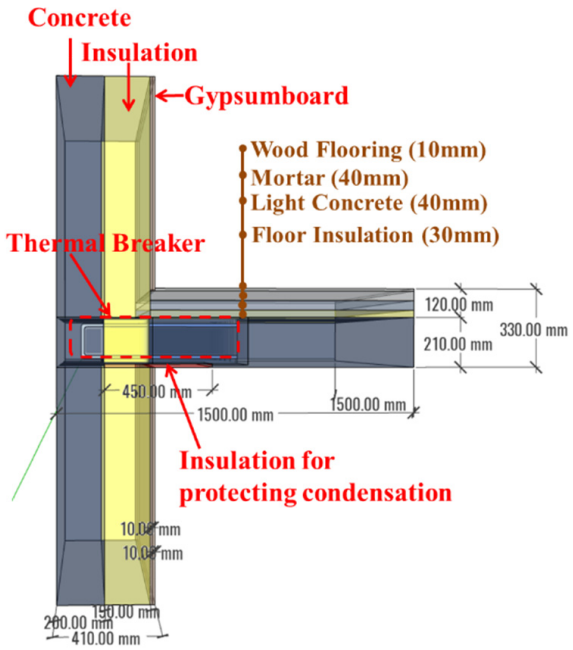


Figure 2. Section of the model for simulation.

Figure 3 presents the three-dimensional model of a thermal bridge breaker at the joint between the slab and wall. The Physibel program, based on ISO 10211 [39], is a building physics software for analyzing heat transfer in building façade elements, and can be used for various applications, such as building energy performance and condensation control [40–43]. Using this software, the present study predicted the surface temperatures of the slab and walls, and calculated the heat loss. To analyze the thermal performance of the developed thermal bridge breaker more accurately, the size of the model created by Physibel was at least 1 m, where the structure and building materials were used for typical residential buildings in South Korea.

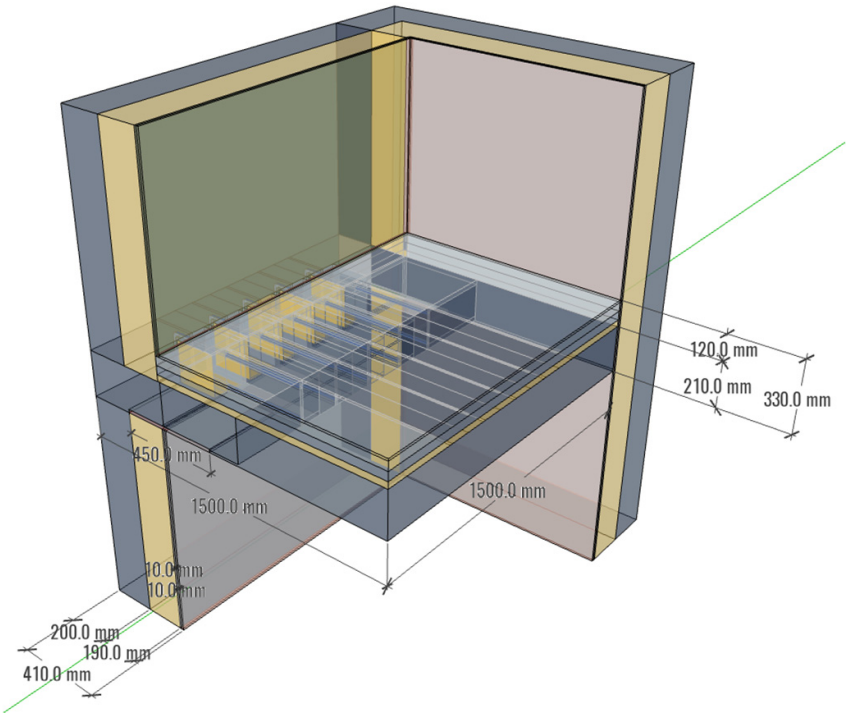


Figure 3. The simulation model.

2.1. Thermal Properties and the Cases

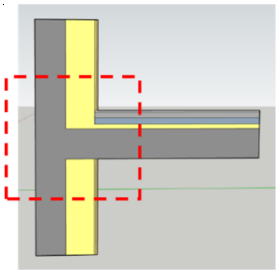
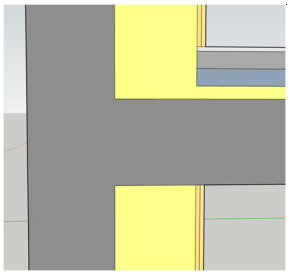
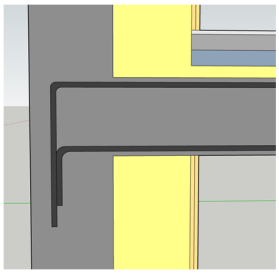
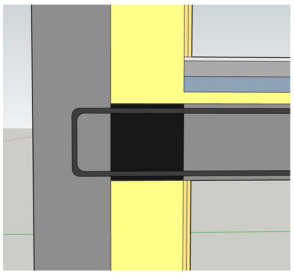
Table 1 and Figure 2 show the thickness and thermal conductivities of the building envelopes. Among these values, the 30 mm thickness insulation for the slab was intended to prevent heat loss, as well as for noise control at the floor construction, based on the building energy standard in South Korea [38].

Table 1. The thermal properties of the building envelopes and the thermal bridge breaker.

	Component	Thickness (mm)	Thermal Conductivity (W/mK)
Exterior Wall	Concrete	200	1.6
	Insulation	190	0.029
	Gypsum board	10 + 10	0.18
Slab	Concrete	210	1.6
	Insulation	30	0.030
	Lightweight Concrete	40	0.16
	Mortar	40	1.4
	Wood flooring	10	0.17
Thermal bridge breaker	Insulation	150	0.025
	Concrete (UHPC)	50	0.2

Table 2 shows the cases for the analysis of the thermal performance of the walls and slabs with/without the thermal bridge breaker and rebar. The thermal performance of the structure was calculated by the thickness and thermal conductivity of the building materials. Case 1 presents the general concrete structure, composed of an exterior wall and a slab. To analyze the thermal influence of rebars, the structure was equipped with rebars (Case 2). In general, the rebars are distributed at regular intervals. For the present study, the simulations were conducted with and without rebars to determine how the rebar can influence the thermal bridge (Case 1 and Case 2). For Case 3, the structure with rebars was equipped with the thermal bridge breaker, as shown in Figure 1. The rebar distribution for Case 2 was based on the guidelines for the construction of residential buildings.

Table 2. Simulation cases.

	Case 1	**Case 2**	**Case 3**
				
Thermal bridge breaker	uninstall	uninstall	install
rebar	uninstall	install	install

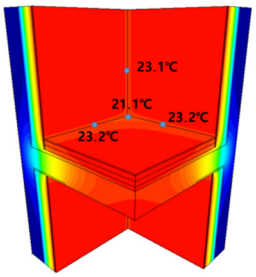
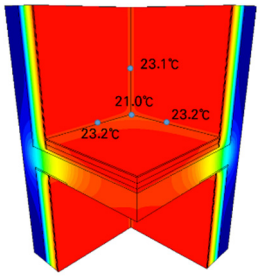
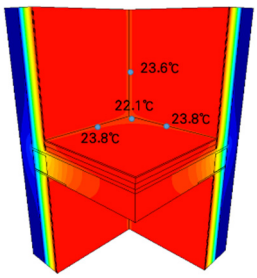
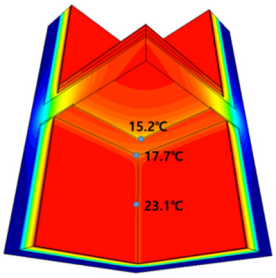
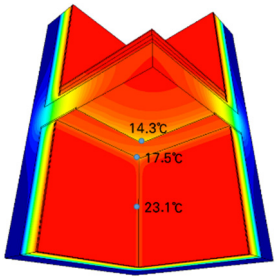
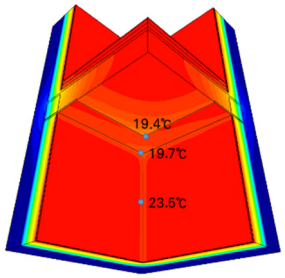
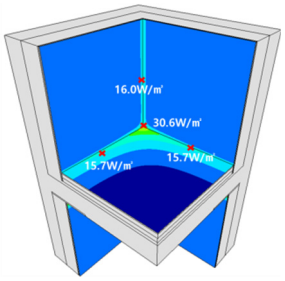
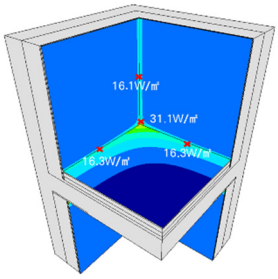
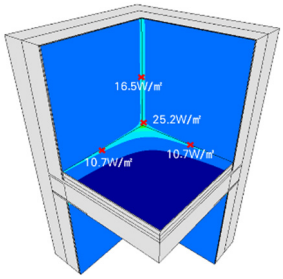
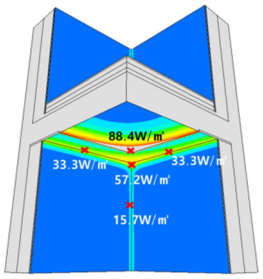
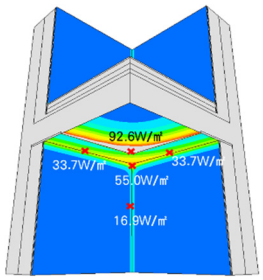
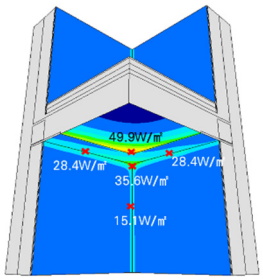
For the simulation condition, the temperatures for the indoor and outdoor were set at 25 °C and −15 °C, respectively. These thermal conditions were based on the design guidelines for residential buildings for preventing condensation in Korea [44].

2.2. Simulation Results

Table 3 shows the interior surface temperatures, heat flow and effective thermal transmittance for each case. As shown in Case 2, the surface temperature for the wall and floor junctions was about 21.0 °C, which was the lowest temperature on the upper part of the model. In addition, the surface temperature of the upper part of Case 2 differed by about 2 °C.

For the lower part of the model, the lowest temperature, about 14.3 °C (Case 2), was observed at the wall and floor junctions, where the end of the insulation was at the ceiling to protect against condensation (width: 450 mm, thickness: 15 mm). It can be observed that condensation can easily occur in this situation, when the relative humidity is above 52%. Moreover, the surface temperatures of Case 2 at the ceiling show about 8.8 °C difference between the floor and wall junctions (14.3 °C), and the corner of the walls (23.1 °C). Furthermore, 92.6 W/m^2 of the heat loss occurred at the wall and floor junctions at the ceiling in Case 2. Compared with Case 3, a large surface temperature difference was observed at the lower part, due to the influence of the thermal bridge breaker, which was 14.3 °C and 19.4 °C for Case 2 and 3, respectively. For residential buildings in South Korea, it can be observed that the installation of the thermal bridge breaker can minimize the heat loss and condensation occurrence at the wall and floor junctions. To analyze the energy consumption using the thermal bridge breaker, the effective thermal transmittance was calculated. When simply calculating the thermal transmittance of the wall in all cases, it was 0.144 W/m^2 K. However, the effective thermal transmittance considering the thermal bridge increased higher about 0.1 W/m^2 K when three-dimensional modeling was used (0.241 W/m^2 K).

Table 3. Simulation results for cases.

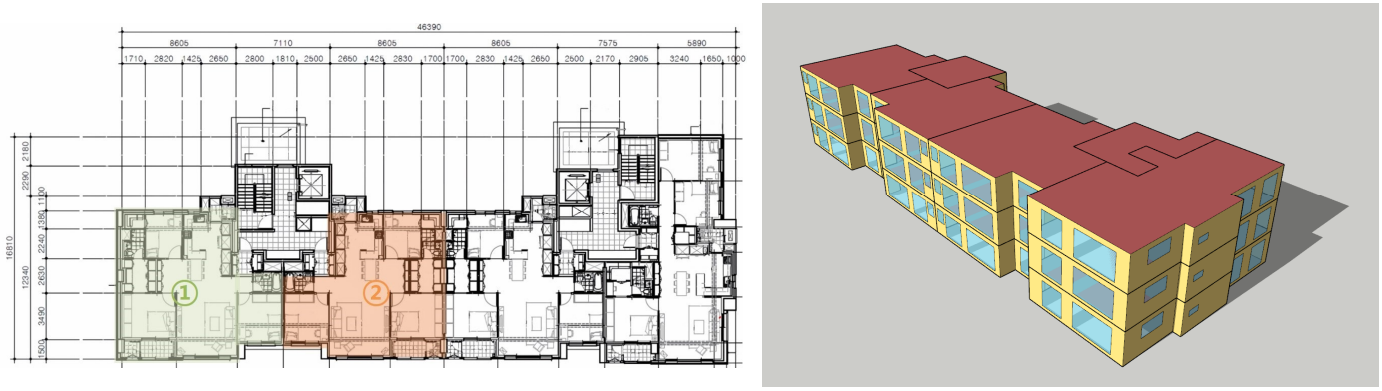
		Case 1	Case 2	Case 3
Surface temperature [°C]	The upper part of the model			
	The lower part of the model			
Heat loss [W/m^2]	The upper part of the model			
	The lower part of the model			
Total heat flow [W]		61.03	62.88	45.29
Effective thermal transmittance [W/m^2 K]		0.234	0.241	0.174

For Case 2, where reinforcing bars were installed, the effective thermal transmittance was 0.241 W/m^2 K. For Case 1, where an assumption was made that no reinforcing bar was installed, it was 0.234 W/m^2 K, which showed that the thermal performance of Case 1 was better than that of Case 2, by 0.007 W/m^2 K. When the developed thermal bridge breaker was equipped in the structure (Case 3), the effective thermal transmittance was 0.174 W/m^2 K. In addition, the effective thermal transmittance in Case 3 was lower than that in Case 2, about 0.067 W/m^2 K. It can be observed that the use of the thermal bridge breaker can have a significant impact on the thermal insulation performance. In the next section, Case 2 and 3 were applied to the apartment building in South Korea, to investigate the energy performance.

3. Heating and Cooling Analysis

3.1. Simulation Setup

To analyze the energy performance of the apartment unit equipped with the thermal bridge breaker, EnergyPlus 9.3.0 was used [45]. Figure 4 shows the plan and three-dimensional view of the residential building for this analysis. The model was created by OpenStudio [46]. As the standard unit size of residential buildings, the size of the unit was 84 m^2 and each floor had four units. To consider the heat transfer among floors, the energy simulation models with three floors were created, and Units ① and ② in the middle of the floors were the main focus for the analysis.



(**a**) (**b**)

Figure 4. The simulation model for the energy analysis. (**a**) Plan; (**b**) 3D view.

It was assumed that the residential building was located in Seoul in South Korea. The other boundary conditions are presented in Table 4. The simulation was conducted over a period of a year.

Table 4. Simulation condition.

Site Location	Seoul (Seoul weather data)
Design Day	−11.4 °C (21 January), 32.1 °C (21 August)
Setpoint Temperature	20 °C (heating), 26 °C (cooling)
Thermal Transmittance	Wall 1 (0.241 W/m^2 K), Wall 2 (0.174 W/m^2 K), Fenestration (0.98 W/m^2 K, SHGC 0.58)
Infiltration	0.12 ACH (air change per hour)
Ventilation	0.5 ACH
Schedule	Residential building schedule
Lighting	3.84 W/m^2

3.2. The Result of the Simulation for Heating and Cooling Analysis

The effective thermal transmittances for the exterior walls in Unit ① in Figure 4 were set to 0.241 W/m^2 K and 0.174 W/m^2 K for heating and cooling loads, respectively. As a result of the simulation, Figure 5 shows the cooling and heating loads for the components at Unit ①. As shown in (a) within Figure 5, the cooling load was measured at 3920 W, when the effective thermal transmittance of 0.174 W/m^2 K was applied to the exterior walls of Unit ①. Through the exterior walls, 159 W was gained, which consisted of 4.1% of the total cooling load. Around 47% of the heat (1840 W) was gained through window systems, and, thus, a way to improve the thermal performance of the window systems is required, in order to reduce the cooling load. In the case of heating, the total heating load was 3577 W, as shown in (b) of Figure 5. An estimated 12% of heat (439 W) was lost through the exterior walls. Specifically, the heat losses from ventilation and infiltration were measured at 64% and 15%, respectively. Additionally, 17% and 5% of the total heating

load were lost through the window system and the entrance door, respectively. Overall, the heating load has different aspects from the cooling load.

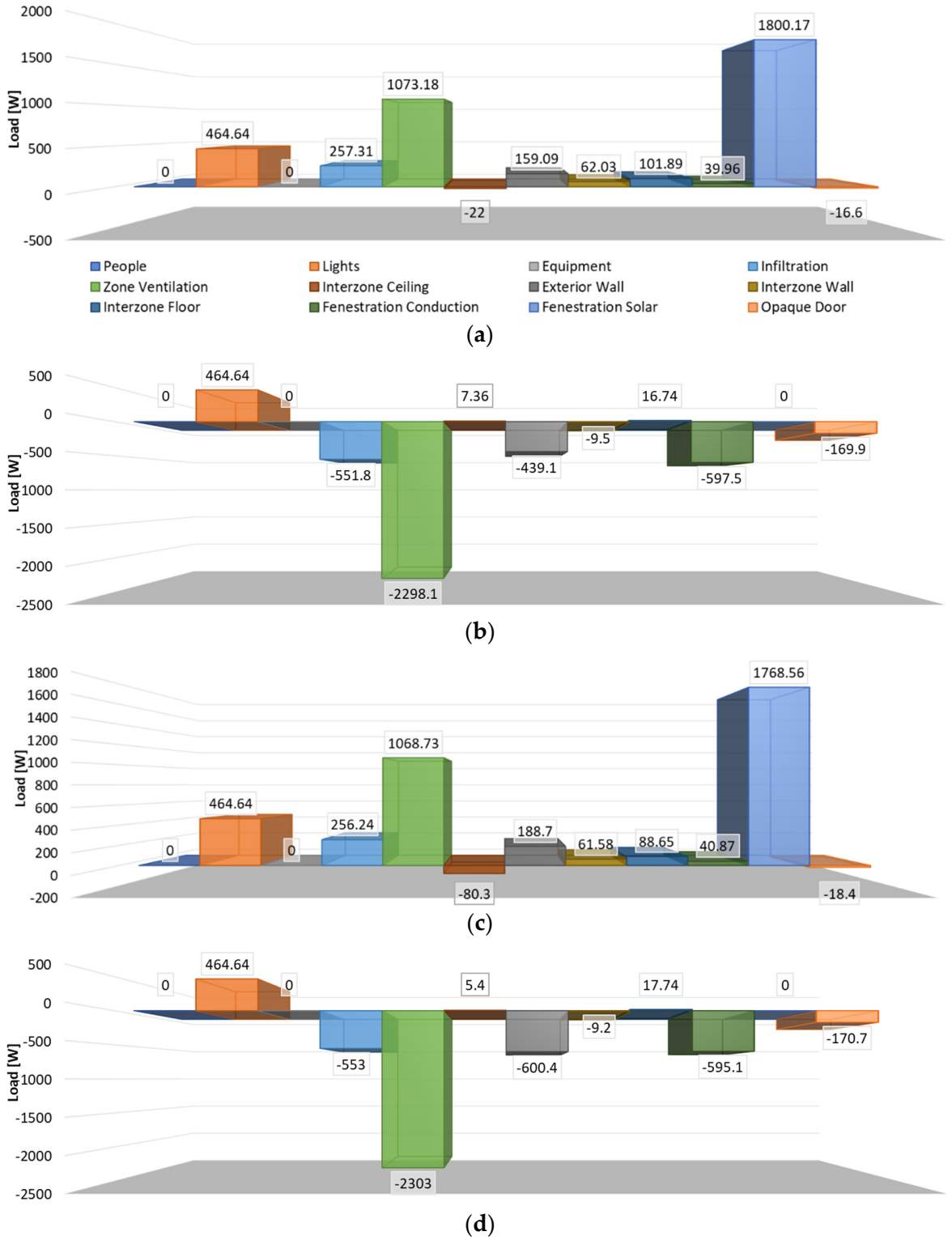


Figure 5. The cooling and heating loads for the units of the residential building by different effective thermal transmittances. (**a**) Cooling load of the unit with the wall's thermal transmittance of 0.174 W/m^2 K; (**b**) heating load of the unit with the wall's thermal transmittance of 0.174 W/m^2 K; (**c**) cooling load of the unit with the wall's thermal transmittance of 0.241 W/m^2 K; (**d**) heating load of the unit with the wall's thermal transmittance of 0.241 W/m^2 K.

To investigate thermal influence through the thermal bridge breaker, a heating and cooling analysis was conducted. The effective thermal transmittance of 0.241 W/m^2 K was applied to Unit ①, without the thermal bridge breaker, while the effective thermal transmittance of 0.174 W/m^2 K was used for Unit ①, which was equipped with the thermal bridge breaker. The heating load for Unit ①, with/without the thermal bridge breaker, was measured at 3744 W and 3577 W, respectively. This reveals that a 4.5% decrease in the heating energy occurred when the thermal bridge breaker was equipped. For cooling energy, an estimated 0.7% increase was observed when the thermal bridge breaker was used. It can be observed that the heat gained through the exterior walls in the summer was smaller than the heat lost through the walls in the winter.

In the case of Unit ②, the size of the exterior walls was 67.8 m^2, while the size of the exterior walls of Unit ① was 100.4 m^2. When the thermal bridge breaker for Unit ② was used, an estimated 2.9% decrease in the heating load was observed. This reveals that the reduction in heating load in the unit equipped with the thermal bridge breaker can be greater when the area of the exterior walls is larger.

Figure 6 presents the cooling and heating loads through the exterior walls with the thermal bridge breaker, since the exterior wall was the main component thermally influenced by the thermal bridge breaker. When the developed thermal breaker was used, the heat gain through the exterior walls in the summer decreased from 188.7 W to 159.1 W, which was about 15.7%. In the winter, the heat loss through the exterior walls was reduced from 600 W to 439 W (about 26.9%). In sum, the use of the thermal bridge breaker can improve thermal performance, such as heating and cooling, by 15–27% for residential buildings equipped with an interior insulating finishing system.

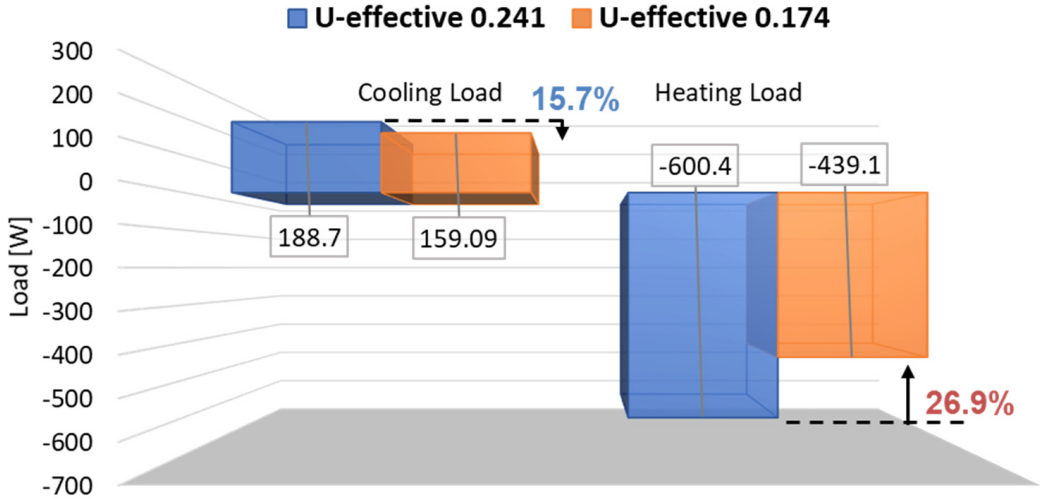


Figure 6. Heat gain and loss with/without the thermal bridge breaker.

4. Conclusions

The present study investigated the thermal and energy performances of the developed thermal bridge breaker for residential buildings constructed using reinforced concrete, to minimize the thermal bridges in building envelopes. By using Physibel, thermal behaviors with/without the thermal bridge breaker, such as interior surface temperatures, heat flow, and effective thermal transmittance, were calculated. Among the cases, the effective thermal transmittance was the lowest when the developed thermal bridge breaker was equipped. It can be observed that the use of the thermal bridge breaker can have a significant impact on thermal insulation performance, as well as improve the thermal performance. In the case of the cooling and heating load analysis, the EnergyPlus program was utilized. In general, heat was greatly lost through the exterior walls in the winter, while heat was significantly gained through the window systems in the summer. When the thermal bridge breaker was equipped, the total heating was decreased by 4.5%, while the cooling load was increased by 0.7%. Specifically, the heating and cooling load through the exterior walls with the thermal

bridge breaker was decreased by 15–27%. Therefore, the use of the thermal bridge breaker can have a significant impact on the thermal insulation performance, and can also reduce the building energy consumption.

Author Contributions: Conceptualization, M.-Y.K. and H.-G.K.; methodology, M.-Y.K.; software, G.H.; formal analysis, H.-G.K.; investigation, M.-Y.K.; resources, J.-S.K.; writing—original draft preparation, G.H.; writing—review and editing, G.H.; visualization, M.-Y.K.; supervision, H.-G.K.; project administration, H.-G.K.; funding acquisition, J.-S.K. All authors have read and agreed to the published version of the manuscript.

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