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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.

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)
COP_{EHP_c}	Coefficient of performance of electric heat pump in cooling mode
COP_{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_{Rsi_min}	Lowest temperature factor
h_o	Outdoor surface heat transfer coefficient (W/m^2K)
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/m2)
T_C	Surface temperature at center of metal panel (°C)
T_i	Indoor air temperature (°C)
T_o	Outdoor air temperature (°C)
T_{si_min}	Lowest indoor surface temperature (°C)
T_{sol}	Sol-air temperature (°C)
T_{TBk}	Surface temperature at thermal bridge (°C)
$\bar{T}_C$	Average surface temperature at center of metal panel (°C)
$\bar{T}_{TBk}$	Average surface temperature at thermal bridge (°C)
$\Delta\bar{T}_{C-TBk}$	Average surface temperature difference between center and thermal bridge (°C)
U_{1-D}	Thermal transmittance assuming one-dimensional heat transfer (W/m^2K)
U_{eff}	Effective thermal transmittance (W/m^2K)
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-