THE OPTIMAL INSULATION DETAIL OF THE THERMAL BRIDGE ADJACENT TO HOT WATER PIPES IN APARTMENT BUILDING SLABS

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ABSTRACT

The methods for evaluating the thermal performance of each insulation detail alternative with the multi-dimensional heat transfer simulation are presented to determine the optimal insulation details of the thermal bridges adjacent to hot water pipes in apartment building slabs. The optimal insulation detail of the side wall-slab joint is presented based on the evaluation of inside surface condensation and life cycle costs.

INTRODUCTION

There are many cases in which the layer of insulation is disconnected by structural components at the joints in apartment building envelope. These joints become thermal bridges at which the risk of inside surface condensation and heat loss increase. Especially at the joints adjacent to hot water pipes for heating (see Fig. 1), the heat loss is so great that the outside surface temperatures are higher by 2～4℃ in the winter than those of surrounding regions.

To improve the thermal performance of these joints, the optimal insulation details should be applied after the evaluation of each insulation detail alternative. If the optimal insulation details are applied to each joint, there is a good chance of energy conservation since apartment buildings are envelope load dominated buildings in which components with similar structures are repeated.

In the existing insulation details of these joints, subsidiary insulation is installed to decrease heat loss. (see Fig. 1) However, there are some cases in which heat loss increases due to misplacement and wrong dimensions of subsidiary insulation. These are attributable to the lack of quantitative thermal performance evaluation methods for the insulation details of the joints where hot water pipes for heating are and where multi-dimensional heat flow path occurs.

Thus, this study aims to present the methods for evaluating the thermal performance of the insulation details of these joints, quantitatively, with the multi-dimensional heat transfer simulation. The optimal insulation detail of the side wall-slab joint is presented based on the evaluation of inside surface condensation and life cycle costs.

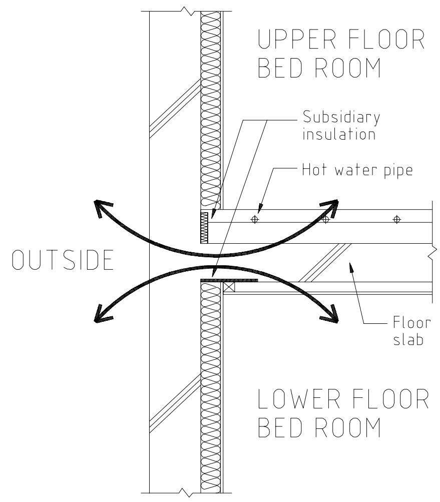

Fig. 1. Side wall-slab joint

THERMAL PERFORMANCE EVALUATION METHODS

As the thermal resistance of the joints increases, the risk of inside surface condensation in the winter and heating cost decrease. Additional benefits may be increased occupant comfort and reduced heating[1]

[1] There is no pre-installed central cooling system in Korean apartment buildings.

system capacity. Since these benefits are difficult to quantify and are likely to be negligible [1], the suggested evaluation methods focus on inside surface condensation and life cycle costs.

INSIDE SURFACE CONDENSATION

Boundary conditions

Inside surface condensation occurs when inside surface temperature is lower than inside air dew point temperature. Since inside air dew point temperature is determined by inside air temperature and relative humidity, inside surface condensation may or may not occur at the same surface temperature. The inside air temperature and relative humidity are varied dramatically according to the location, heating method, extent of insulation, and way of life. Thus, it is necessary to set the standard inside air temperature and relative humidity conditions for the evaluation. As the outside air temperature drops, the inside surface temperature will drop accordingly. Concerning outside air temperature, the safest evaluation results can be obtained if the worst condition is applied. In this study, the standard inside air temperature and relative humidity, and the lowest outside air temperature of Seoul are determined on the basis of the conditions in KSF2295, Korean Standard on *the Method of Testing for Condensation at Windows and Doors*. (see Table 1)

Table 1. The standard condition for the evaluation of inside surface condensation (KSF2295)

Inside air temperature	Inside air relative humidity	Inside air dew point temperature	Outside air temperature (Seoul)
20℃	50%	9.3℃	-15℃

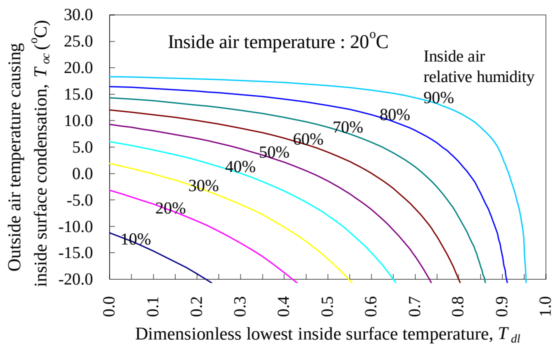

Fig. 2. Outside air temperature causing inside surface condensation

On the inside surface of the joints, heat transfer coefficient decreases due to the drop in air speed. If the heat transfer coefficient on the inside surface decreases when inside surface temperature is lower than inside air temperature, the inside surface temperature becomes lower. Thus, the risk of inside surface condensation increases. In this study, a heat transfer coefficient of 3.5 W/m^2℃ is used on the inside surface. [2]

Evaluation methods

It can be determined whether the inside surface condensation may or may not occur by comparing the lowest inside surface temperature (T_l) to the inside air dew point temperature (9.3℃) of the standard condition. The lowest inside surface temperature (T_l) for the standard condition can be found by the steady state heat transfer analysis. Apartment buildings are residential buildings with continuous night time heating. Thus, the steady state heat transfer analysis is a safe analysis method to get the lowest inside surface temperature.

The lowest inside surface temperature (T_l) can be represented as the dimensionless lowest inside surface temperature (T_{dl}) as in Eq. (1). [3] If the lowest inside surface temperature (T_l) is substituted with the inside air dew point temperature (T_c) after the rearrangement of Eq. (1) to Eq. (2), the outside air temperature at which the inside surface condensation will occur (T_{oc}) can be found. It is then possible to evaluate the inside surface condensation for any combination of the inside air temperature (T_i), relative humidity, and outside air temperature (T_o).

$$T_{dl} = \frac{T_l - T_o}{T_i - T_o} \qquad (1)$$

$$T_o = \frac{T_{dl} \times T_i - T_l}{T_{dl} - 1}, \; T_l \Rightarrow T_c \qquad (2)$$

The outside air temperature at which the inside surface condensation will occur (T_{oc}) to the dimensionless lowest inside surface temperature (T_{dl}) is presented in Fig. 2 when the inside air condition is 20℃ and 10～90% (R.H.).

LIFE CYCLE COST

Economic factors related with the thermal performance of the insulation detail are material, labor, cooling, heating, and maintenance costs. Life cycle costs are the sum of these costs during the life time including construction period. If the life cycle costs trend of each insulation detail alternative can be found, it is possible to determine the economically optimal insulation detail of the joints.

To calculate the life cycle costs of each insulation detail alternative, it is necessary to quantify the costs of all economic factors. However, there is no central cooling system in Korean apartment buildings. Occupants use electric fans or room air conditioners for cooling depending on individual choice. Thus, it is difficult to quantify the cooling cost due to the heat gain through the joints. According to the survey of management expenses of 1,896 apartment buildings in Korea, annual cooling cost in 1996 is only 4.7% of total expenses related to energy use. [4] So, it is expected that the cooling cost due to the heat gain through the joints is so small and negligible. Considering the occupants' convenience, insulation detail alternative that needs repair or replacement

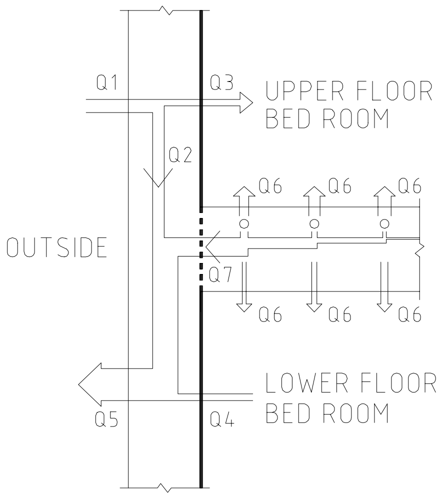

Fig. 3. Heat flow at the joints

Table 2. Hot water supply schedule for heating [2]

Daily lowest outside air temperature (℃)	Heating time	Hot water temperature (℃)
below -15	4~7, 11~13, 17~20	65
-15~-10	3~6, 11~13, 17~20	65
-10~-5	4~6, 11~13, 17~20	65
-5~15	4~6, 17~19	65

[2] In Korean apartment buildings, intermittent heating is generally applied.

during the life time cannot be taken into account. So, it is possible not to consider the maintenance cost. In this study, cooling and maintenance costs are not considered in calculating the life cycle costs of each insulation detail alternative.

Each insulation detail alternative can be assumed to have the same labor cost, when there is no difference in the amount of work and the process of construction. If the same amount of cost is added to or subtracted from the life cycle costs of each insulation detail alternative, life cycle costs trend is not changed. In this study, labor cost is not considered in determining the economically optimal insulation detail when each alternative can be assumed to have the same cost.

Heating cost

Heating cost during the life time can be calculated by annual heating cost multiplied by present value coefficient. To calculate annual heating cost, annual heat loss through the joints should be known. To calculate the annual heat loss through the joints, multi-dimensional unsteady state heat transfer simulation is performed.

To evaluate each insulation detail alternative correctly, annual heat loss through the joints should be calculated while applying actual hot water supply schedule for heating. Heat flow at the joints adjacent to hot water pipes in heating is presented in Fig. 3. Q1 and Q5 are heat gain and loss on the outside surface, respectively. Q2 is heat loss from the stored heat in envelope. Q3 and Q4 are heat gain and loss on the inside surface, respectively. Q6 and Q7 are heat gain and loss from hot water pipes, respectively. In this study, annual sum of Q4 and Q7 are defined as annual heat loss through the joints. Boundary for calculating annual heat loss is represented by the thick solid and dotted lines in Fig. 3. The generalized hot water supply schedule for heating in Korean apartment buildings is presented in Table 2.

In calculating annual heat loss with the multi-dimensional unsteady state heat transfer simulation, it is inefficient to model the whole building envelope. To evaluate each insulation detail alternative, the region affected by the thermal bridge can be isolated from the remainder of the building envelope by identifying a set of adiabatic planes. [5] In this study, the effective calculation domain, namely the effective isolated portions of envelope to be included in the simulation model, is defined to make the heat transfer analysis practical.

In the slab (see Fig. 4), heat loss from hot water pipes (Q7) does not increase any more, if the calculation domain is extended beyond a certain limit. In the side wall (see Fig. 4), heat flow path becomes one dimensional beyond a certain limit at which there are no effects from the excessive heat loss at the thermal bridge. The effective calculation domains are extended to these limits in the slab and the side wall.

The effective calculation domain will be varied according to the extent of insulation, outside and hot water conditions. For safety, the effective calculation domain is selected when it is most extended considering no subsidiary insulation, the lowest outside air temperature, and hot water is supplied. Finally the effective calculation domain is determined by the steady state heat transfer analysis.

Annual heating cost (C_{hjoint}) due to the annual heat loss through the joints (Q_{joint} = Q4 + Q7) can be calculated by Eq. (3).

$$C_{hjoint} = \frac{Q_{joint} \times UnitC_{fuel}}{\varepsilon} \qquad (3)$$

The unit cost per MJ of the fuel (diesel) for heating ($UnitC_{fuel}$) is estimated to 6.84E-03$/MJ on the basis of the cost in Korea, 1996. The efficiency of the heating system in Korean apartment buildings (ε) is estimated to 0.597. [6]

Life cycle costs

Life cycle costs of each insulation detail alternative (LCC_{joint}) are the sum of the initial costs (C_{ijoint} = material cost + labor cost) and the present value of heating cost during the useful life time. Life cycle costs of each insulation detail alternative can be calculated by Eq. (4).

$$LCC_{joint} = C_{ijoint} + \frac{C_{hjoint}(1+r)\{(1+r)^n - 1\}}{r} \qquad (4)$$

Real interests rate (r) and life time (n) are estimated to 2.27% and 30years, respectively. [7][8]

THE OPTIMAL INSULATION DETAIL

The side wall-slab joint is selected for developing the optimal insulation detail. Heat transfer analysis is performed with the finite difference multi-dimensional steady and unsteady state heat transfer analysis program, HEATrans v.8. [9] Thermal properties of all materials are assumed to be constant. Contact resistances at the interfaces between materials are neglected.

In evaluating the inside surface condensation, a heat transfer coefficient of 34W/m^2℃ is used on the outside surface. In calculating the annual heat loss, room temperature is set to 23 ℃, hot water temperature to 65℃, sol-air temperatures [1], and outside surface heat transfer coefficients applying the algorithm in DOE-2 [10] are used. Calculation time step is 15 minutes and the standard weather data of Seoul is used. Heat losses in July and August (non-heating periods) are excluded in calculating the annual heating cost.

Each insulation detail alternative is assumed to have the same labor cost, since there is little difference in the amount of work and the process of construction. (see Fig. 6 and Table 3) Material and heating costs are calculated, when each alternative is constructed in the length of 9.2m, that is the length of side wall. Heat flow stream lines and the effective calculation domain in the side wall-slab joint are presented in Fig. 4. The lowest outside air temperature of -15℃ in Seoul is used.

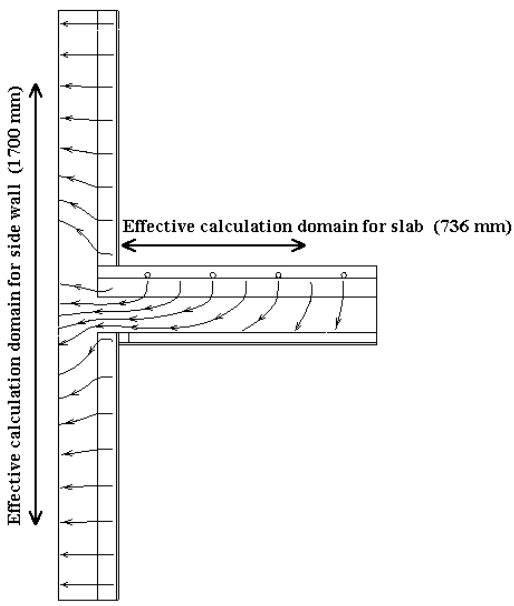

Fig. 4. Effective calculation domain

ALTERNATIVES AND EVALUATION RESULTS

Existing sectional insulation detail of the side wall-slab joint is presented in Fig. 5. In this joint, region A and B are thermally defective areas. The insulation detail of region A adjacent to hot water pipes has a great influence on the heat loss. Firstly the optimal insulation detail of region A is determined without subsidiary insulation for region B. Then the optimal insulation detail of region B is determined while applying the optimal insulation detail of region A.

Optimal insulation detail of region A

Insulation detail alternatives for region A are presented in Fig. 6.[3] According to the evaluation results (see Table 4), alternative 3 is the optimal insulation detail of region A. The lower part of the gypsum board is away from the concrete slab because of the difference between the gypsum board dimensions and the floor height.

Optimal insulation detail of region B

Insulation detail alternatives for region B are evaluated through 3 steps. (see Table 3) In step 1, alternatives are prepared to determine the optimal thickness of subsidiary insulation. (alternative 8 ~ 13) In step 2, alternatives are prepared to find the range where the optimal width of subsidiary insulation exists. (alternative 14 ~ 16) In step 3, alternatives are prepared to determine the optimal width of subsidiary insulation. (alternative 17 ~ 19)

In step 1, it is found that the alternatives with the subsidiary insulation thickness of 10mm are more economical. (see Fig. 7) In step 2, it is found that the optimal width of subsidiary insulation exists between 200mm and 500mm. (see Fig. 8) In step 3, the life cycle costs are minimized at the subsidiary insulation width of 318.85mm from the regression analysis result. (see Fig. 9) The regression equation is $y = -4.3925E\text{-}07x^3 + 6.0649E\text{-}04x^2 - 2.5279E\text{-}01x + 1.5872E+03$. ($R^2$=9.9899E-01, F-value=1.9955E+03, P-value=1E-04) In the optimal insulation detail (see Fig. 10), the subsidiary insulation width of 300mm is adopted instead of 318.85mm for the convenience of construction and the economical use of insulation materials considering the manufactured size.

[3] An external insulation method is not used due to the extremely high initial costs in Korea. The main insulation thickness is prescribed by law.

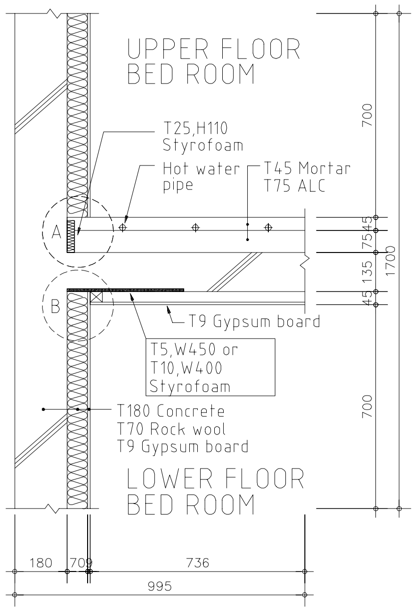

Fig. 5. Existing sectional insulation detail

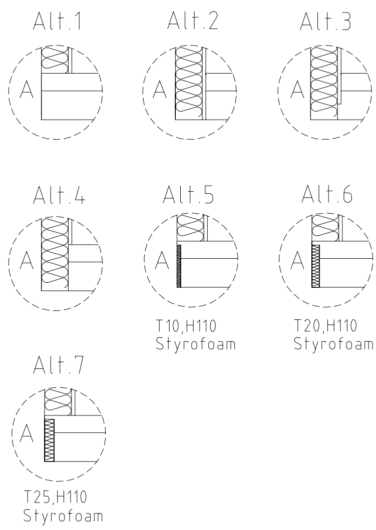

Fig. 6. Alternatives for region A

Table 3. Alternatives for region B

No. of alternatives		8	9	10	11	12	13
Subsidiary insulation dimensions (mm)	Thick-ness	5	5	5	10	10	10
	Width	200	400	600	200	400	600
No. of alternatives		14	15	16	17	18	19
Subsidiary insulation dimensions (mm)	Thick-ness	10	10	10	10	10	10
	Width	100	300	500	250	350	450

THE OPTIMAL INSULATION DETAIL

The optimal insulation detail of the side wall-slab joint is presented in Fig. 10. Fig. 11 and Fig. 12 show the distribution of the temperature and the standard inside air dew point temperature (9.3℃) in the joint during heating. The inside surface condensation does not occur under the standard condition. (see Fig. 12) The dimensionless lowest inside surface temperature (T_{dl}) is 0.84. Thus, it can be said that inside surface condensation never occurs in the optimal insulation detail in Seoul below an inside air relative humidity of 70% when the inside air temperature is 20℃. (see Fig. 2)

Fig. 13 and Fig. 14 show the distribution of the temperature and the standard inside air dew point temperature (9.3℃) in the joint while not heated. The inside surface condensation does not occur under the standard condition. (see Fig. 14) The dimensionless lowest inside surface temperature (T_{dl}) is 0.79. Thus, it can be said that inside surface condensation never occurs in the optimal insulation detail in Seoul below an inside air relative humidity of 63% when the inside air temperature is 20℃. (see Fig. 2)

Evaluation results of each insulation detail alternative are presented in Table 4. The life cycle costs of alternative 3 are smaller by 11.76% than those of alternative 1 which has no subsidiary insulation. The life cycle costs of alternatives for region B are smaller by 1～2% than those of alternative 3 which has no subsidiary insulation in region B. Thus, the insulation detail of region A adjacent to hot water pipes is more important to reduce the life cycle costs.

Even though the widths of subsidiary insulation for region B in alternatives 10 and 13 are wider than those in alternatives 9 and 12, heating cost increases on the contrary. This is resulted from the fact that the subsidiary insulation blocks the heat transfer from hot water pipes to the room in the lower floor. (see Q6 in Fig. 3). This means that heat loss increases on the contrary beyond a certain width of subsidiary insulation. Thus, the optimal subsidiary insulation width of 300mm should be applied to this joint.

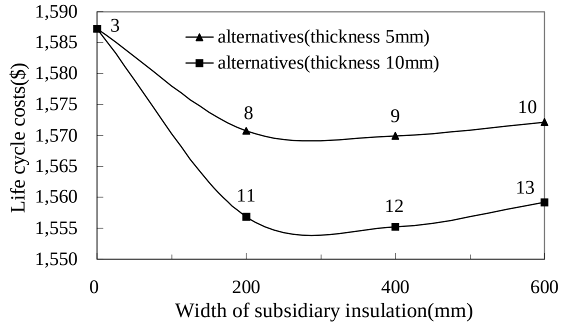

Fig. 7. Life cycle costs trend in step 1

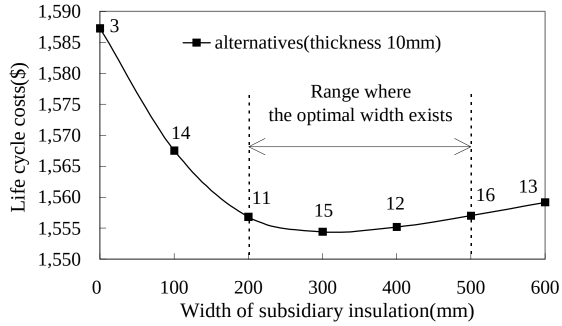

Fig. 8. Life cycle costs trend in step 2

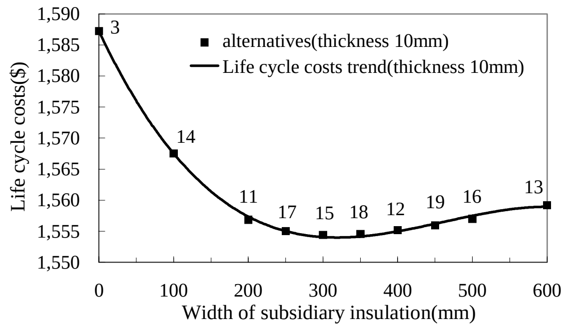

Fig. 9. Regression analysis result in step 3

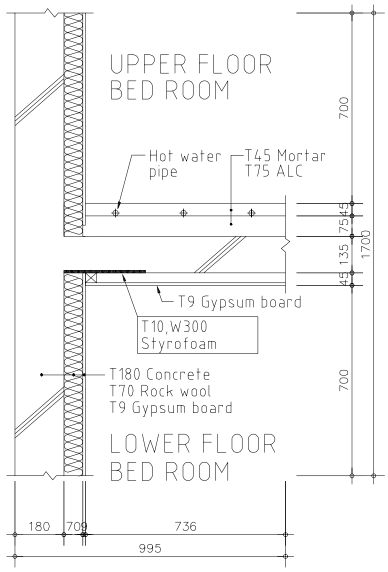

Fig. 10. The optimal insulation detail

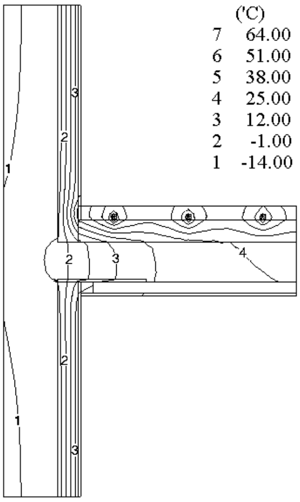

Fig. 11. Temperature distribution during heating

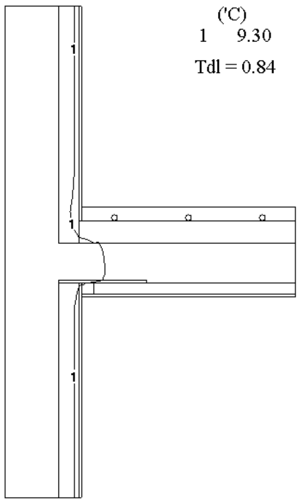

Fig. 12. Standard inside air dew point temperature distribution in the joint during heating

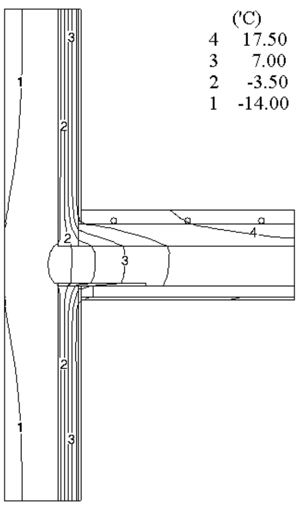

Fig. 13. Temperature distribution while not heated

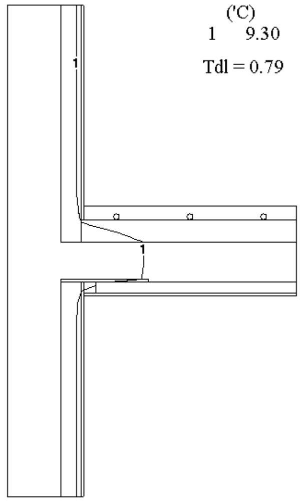

Fig. 14. Standard inside air dew point temperature distribution in the joint while not heated

Table 4. Evaluation results

No. of alter-natives		Inside surface condensation while not heated (O : occur, × : not occur)		Initial (mate-rial) cost ($)	Heating cost during life time ($)	Life cycle costs ($)	Life cycle costs varia-tion rate (%)
		upper corner	lower corner				
A	1	O	O	356.18	1,442.56	1,798.74	100.00
	2	×	×	356.72	1,237.44	1,594.15	88.63
	3	×	×	355.83	1,231.41	1,587.24	88.24
	4	×	×	356.21	1,236.12	1,592.32	88.52
	5	×	×	362.24	1,335.79	1,698.04	94.40
	6	×	×	361.70	1,302.83	1,664.53	92.54
	7	×	×	361.36	1,291.92	1,653.28	91.91
B	8	×	×	355.70	1,215.03	1,570.72	87.32
	9	×	×	355.79	1,214.14	1,569.93	87.28
	10	×	×	355.89	1,216.24	1,572.13	87.40
	11	×	×	355.79	1,201.04	1,556.83	86.55
	12	×	×	355.98	1,199.20	1,555.18	86.46
	13	×	×	356.17	1,203.00	1,559.17	86.68
	14	×	×	355.70	1,211.83	1,567.52	87.15
	15	×	×	355.89	1,198.52	1,554.40	86.42
	16	×	×	356.08	1,200.93	1,557.00	86.56
	17	×	×	355.84	1,199.18	1,555.02	86.45
	18	×	×	355.93	1,198.61	1,554.54	86.42
	19	×	×	356.03	1,199.91	1,555.94	86.50

ACKNOWLEDGEMENTS

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CONCLUSIONS

The joints adjacent to hot water pipes in apartment building slabs become thermal bridges. To improve the thermal performance of these joints, the optimal insulation details should be applied after the evaluation of each insulation detail alternative.

This study presents the methods for evaluating the thermal performance of insulation detail alternatives quantitatively using the multi-dimensional heat transfer simulation. The optimal insulation detail of the side wall-slab joint is presented based on the evaluation of inside surface condensation and life cycle costs. As results, thermal bridging effects are reduced and the life cycle costs are minimized.

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NOMENCLATURE

T_{dl}	Dimensionless lowest inside surface temperature
T_l	Lowest inside surface temperature (℃)
T_o	Outside air temperature (℃)
T_i	Inside air temperature (℃)
T_c	Inside air dew point temperature (℃)
T_{oc}	Outside air temperature at which the inside surface condensation occurs (℃)
Q1	heat gain on the outside surface
Q2	heat loss from the stored heat in envelope
Q3	heat gain on the inside surface
Q4	heat loss on the inside surface
Q5	heat loss on the outside surface
Q6	heat gain from hot water pipes
Q7	heat loss from hot water pipes
C_{hjoint}	Annual heating cost ($)
Q_{joint}	Annual heat loss (MJ)
$UnitC_{fuel}$	Unit cost per MJ of the fuel for heating ($/MJ)
ε	Efficiency of the heating system
LCC_{joint}	Life cycle costs ($)
C_{ijoint}	Initial costs ($)
r	Real interests rate (%)
n	Life time of apartment buildings (year)