Heat transfer analysis and thermal bridge elimination of composite thermal insulation exterior wall adjacent to steel column

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Abstract. Steady-state heat transfer of built-in composite insulation walls close to column had been investigated in this paper by using finite element analysis (FEA). Firstly, the thicknesses of the wall and the thermal insulation were determined according to energy saving requirement of 75%. The heat transfer of the wall with the commonly used details was studied and it was found although adding local insulation on the outside of the column can improve the heat flow concentration, there is still a thermal bridge at the junction of the wall and the column. Then the influence zone of the thermal bridge was investigated and a construction measure of extending the local insulation width was proposed based on the analysis results. Lastly, the partial thermal insulation extended widths for different column sections and thermal insulation were suggested to break thermal bridge completely, which can meet the energy saving requirement of Beijing government.

Keywords: Steel structure building, composite insulation, built-in wall, thermal bridge, influence zone of thermal bridge, heat transfer coefficient.

1. Introduction

Building energy consumption accounts for about 1/3 of the total energy consumption of the society. The composite insulation wall formed by light masonry with additional insulation layer has good thermal insulation performance and economy, and is widely used in construction engineering. Compared with the outsourcing masonry envelop structure, the light block embedded in the frame beam and frame column, is simple and convenient in construction. However, a thermal bridge forms at the part adjacent to beam and column due to the weakened insulation layer, which causes additional loss of building energy consumption. The thermal conductivity of steel is much higher than that of concrete, so the energy consumption of thermal bridge in steel structure buildings becomes more prominent.

Break Bridge is a method to reduce influence of building thermal bridge, which is to use special materials or construction technology to cut off or reduce the impact of the thermal bridge [1]. The methods to break thermal bridge can be classified into three types: partial outsourcing, web perforation and thermal blocking. A layer of rigid foam board was wrapped on the surface of the steel column to
prevent violent heat exchange between steel and surrounding materials in ORNL (Oak Ridge National Laboratory) [2]. Han et al. [3] and Zhou et al. [4] increased the thermal resistance of the steel column by adding local insulation to the steel column. Way et al. [5] extended the heat transfer path by grooving the steel web, and the equivalent heat transfer coefficient became 1/10 ~ 1/5 of the original value, but the compression performance was reduced by 30%. Wu and Zhang et al. [6] analyzed the insulation performance of the composite wall with web perforated light-gauge steel column with insulation layer, and found that the wall had a significant energy saving effect. The U.S. department of energy designs a non-metallic thermal resistance material in the wall to reduce the thermal bridge effect, but the mechanical properties and thermal conductivity of the materials are strictly required [7]. The FSEC (Florida Solar Energy Center) combined two sections of steel with a fiberboard (OSB) to create a wood/steel composite column that increased thermal resistance by 39% [2]. Generally speaking, web perforation is suitable for light-gauge steel composite wall. Due to the complicated construction and weak strength, there are few researches on the thermal insulation structure of steel column in China. The structure of external partial insulation is relatively simple and has good applicability.

Steady heat transfer of steel column thermal bridges with built-in exterior wall in cold northern regions is analyzed by using a FEA software ABAQUS in the present study. Firstly, the thickness of the exterior wall and insulation is designed according to the requirement of 75% energy saving. Secondly, the heat transfer performance of the commonly used configuration close to column was analyzed. It is found that although adding partial insulation outside the column could improve the heat flow concentration, there is still a thermal bridge between the wall and the column. Therefore a new construction measure is put forward based on the analysis results. Thirdly, the feasibility of the break bridge proposed is discussed by changing the form of the column section and the material of insulation. Finally, some conclusions are drawn according to the analysis results.

2. Analysis methods

2.1. Analysis model

A typical practice of the embedded composite insulation wall is shown in Fig. 1. The wall is constructed with light blocks, and the external insulation material is fixed on the wall with binder or anchor bolt. The inner cavity of H-shaped steel column is filled with light block, and the space between the outer insulation layer and the column is filled with light block or other thermal insulation materials. The gap (about 2cm) between the wall and the steel column is filled with light materials. Steel bars are laid at a certain height to strengthen the connection between walls and columns [8].

The H-shaped steel column and adjacent walls are taken as the model (Fig. 2) for steady-state heat transfer analysis. The wall thickness is \( t_w \) and the length \( L \) was greater than \( 2t_w \), which allowed the analysis error to be controlled within 3% [9]. In order to simplify the analysis, the influence of the facing layer, the reinforcement and the light material filling layer between the wall and the column are ignored in the model. The widely used aerated concrete block is selected as the main material of the wall, and the insulation material is fireproof glass wool (Grade A). The thickness of the insulation layer and the partial insulation layer outside the column are \( t_1 \) and \( t_2 \), respectively.

*Figure 1. A typical composite insulation built-in walls*
2.2. Finite element model

A large commercial FEA software ABAQUS is used to carry out the heat transfer analysis. The four-node quadrilateral heat conduction element DC2D4 is used for simulation of the section steel column, masonry and insulation layer. The meshed FE model is shown in Figure 2. The thermal conductivity of the materials is shown in Table 1. The influence of heat radiation is not taken into account, but the heat conduction between materials is considered. The heat is assumed to transfer fully between different materials. The third boundary condition of heat transfer is adopted. The indoor and outdoor convection heat transfer coefficients applied are 8.7 W/(m²·K) and 23.0 W/(m²·K), respectively. The indoor and outdoor temperatures are 18 ℃ and -7 ℃, respectively. The relative humidity of air is 60%, and the indoor dew point is 10.1 ℃ [10].

| Material          | Steel | Aerated concrete | Glass wool |
|-------------------|-------|------------------|------------|
| Heat conductivity W/(m·K) | 58.2  | 0.20             | 0.04       |

2.3. Validation of finite element model

In order to validate the finite element model, the experiment in the literature [11] is used for analysis. The thermal performance and meteorological parameters of exterior wall were measured by using heat flow meter. The wall structure tested is shown in Fig. 3. The indoor and outdoor temperatures were 11.98 ℃ and -17.33 ℃, respectively. The comparison between the tested temperature and the analysis results of a, b and c is shown in Table 3. The results of FLUENT software analysis in the literature [11] are also listed in the table. As can be seen from the table, the analysis results are basically consistent with the test results and the numerical results in the literature, suggesting that the above method can be applied to the heat transfer analysis of the wall.

3. Design of the insulation thickness \( t_1 \)

According to the exterior wall heat transfer coefficient (Table 4) specified by Energy-saving Design Standard for Residential Buildings (DB11/891-2012) [12] and Energy-saving Design Standards for Residential Buildings in Severe and Cold Areas (JGJ 26-2010) [13], the thickness of wall is required to be 413 mm~540 mm if the aerated concrete block is used as insulation alone, which is calculated on
one-dimensional heat transfer theory. It is more suitable to use composite insulation measures, so the thickness of aerated concrete block $t_{bw}$ is assumed as 250 mm, the length of the wall $L$ is 700 mm, the thickness of the glass wool insulation layer is calculated as $t_1 = 60$ mm. $L > 2t_{bw}$, meets the requirements of analysis precision.

| Location                                | a  | b  | c  |
|-----------------------------------------|----|----|----|
| Test results [11]                       | 5.55 | 7.00 | 7.31 |
| Numerical results [11]                  | 5.98 | 7.53 | 7.76 |
| FEM results of the present study        | 5.98 | 7.53 | 7.75 |
| Errors of the present study /%          | 7.7  | 7.6  | 6.0  |

Table 3. Limits of heat transfer coefficient specified by Beijing city /W/(m²·K)

| Number of story | ≤3   | 4~8  | ≥9   |
|-----------------|------|------|------|
| Limit of heat conductivity              | 0.35 | 0.40 | 0.45 |

4. Influence of partial insulation thickness $t_2$

Fig. 4a and Fig. 4b are the contour of temperature and heat flux of the models with $t_2 = 0$ mm (without partial insulation) and $t_2 = 40$ mm, respectively. It is found from Fig.4 that the isotherm of the wall far away from the column tends to the same level, and the temperature gradient of the outside of the column flange is obvious. The web of section of the steel column has a mass flow and is the main channel of heat transfer. After adding partial insulation, the temperature distribution of the junction between the steel column and the wall tends to be uniform, but there is still a significant temperature change.

![Figure 4](image-url)

**Figure 4.** Contour of temperature and heat flux of wall close to column

The influence of $t_2$ on the thermal performance of the wall, is given in Fig.5. Fig. 5a and Fig. 5b are the surface temperature and heat flux at different positions, and the abscissa is the distance from the position to the column. As can be seen from Fig. 5a, the external temperature of the wall inside the column gradually decreases with the increase of $t_2$, while other parts tend to be that of the main wall. The critical temperature of thermal bridge calculated by using ISO standard (calculation method is included in the section 5.1, and the area above the critical temperature is in the influencing area of thermal bridge. With the increase of $t_2$, the influencing area of thermal bridge decreases gradually and the energy saving decreases gradually. When $t_2$ is less than 30mm, both the columns and adjacent walls are in the thermal bridge. However, if $t_2$ is greater than 60mm, only the junction between the column and the wall is in the thermal bridge. It can be seen from Fig. 5b that the heat flux distribution on the surface of the wall is roughly the same as the temperature distribution. When $t_2 = 0$, the heat flux on the outer surface of the wall inside the column is significantly concentrated, about 1.55 times that of the main wall, and the heat transfer coefficient of the column was 0.624W/(m²·K), about 1.78 times that of the main wall. When $t_2 = 40$ mm, the heat flux of the column is equal to that of the main wall. When $t_2$
= 100 mm, the thermal bridge of the wall is almost eliminated. The heat flux of the wall adjacent to the column is higher than that of the main wall.

Figure 5. Influence of \( t_2 \) on thermal performance of the wall

The heat transfer coefficient calculated by using different \( t_2 \) is shown in Fig. 5c. The additional energy consumption of the thermal bridge is taken into account. The limit of the heat transfer coefficient of the exterior wall of 75% energy saving in Beijing is also shown in the figure. It can be see that the heat transfer coefficient gradually decreases as increase of \( t_2 \). When \( t_2 \) takes 68 mm, 48 mm and 35mm, it can meet the requirement of 75% energy saving for buildings with stories \( \leq 3 \), 4~8 and \( \geq 9 \), respectively. Furthermore, the heat transfer coefficient of the wall with \( t_2 = 100 \text{mm} \) is 0.290 W/(m²·K), which meets the requirements of energy saving, but it caused the waste of insulation materials.

The thickness of partial insulation has little effect on the lowest indoor temperature. When \( t_2 \) varies from 0mm to 70mm, the indoor temperature of the corresponding position of the column web is the lowest. When \( t_2 \) is more than 70mm, the indoor temperature of the column web is higher than that of the main wall, and the position with the lowest temperature appears in the main wall. The lowest indoor temperature of the composite insulation wall is 16.30 °C ~ 17.02 °C, which is greater than the dew point temperature 10.1 °C.

5. Optimization of insulation

5.1. The influence zone of thermal bridge

The influence area of thermal bridge given by ISO [14] refers to the area meeting the following conditions:

\[
\frac{1 - \xi_e}{1 - \xi_e} < 0.95 \quad (1)
\]

\[
\xi_e = \frac{t_i - t}{t_i - t_e} \quad (2)
\]
\[
\xi' = \frac{t_i - t'}{t_i - t_e}
\]  

Where, \(t_i\) and \(t_e\) are the indoor and outdoor temperatures, respectively; \(t\) is the temperature of the normal part of the main wall, and \(t'\) is the temperature of the part to be calculated.

5.2. Influence of column section on thermal bridge

Taking \(t_2 = 40\) mm and \(t_1 = 60\) mm, and the other parameters remain unchanged, the thermal performance of the walls with vary H-shaped steel columns is investigated. The temperatures of the outer surface of the wall are given in Figure 6. It can be seen that H-shaped steel columns of different specifications have little influence on the temperature distribution of the outer surface of the wall. \(B\), the width of influence zone of thermal bridge predicted by ISO method is given in Table 4. All of \(B\) are basically about 230 mm. It can be considered that under the same insulation structure, the section size of H-shaped steel column has little influence on the width of influence zone of thermal bridge.

![Figure 6. Influence of column section on outside surface temperature of walls](image)

| Section of column       | \(B\)/mm | Section of column       | \(B\)/mm |
|-------------------------|----------|-------------------------|----------|
| H200×200×8×12           | 231      | H250×250×9×14           | 231      |
| H300×300×10×15          | 230      | H350×350×12×19          | 231      |
| H400×400×13×21          | 228      |                         |          |

5.3. Extended partial insulation

According to the above analysis, it is found that when the partial insulation thickness \(t_2\) is equal to 40 mm, the width of the influence area of thermal bridge is about 230 mm. Therefore, the partial insulation can be extended to 230 mm to break the thermal bridge at the junction of the wall and the column. The temperature distribution of the outer surface of the walls with \(t_2 = 40\) mm, and with \(t_2 = 40\) mm and 230 mm extension is shown in Fig. 7a. As can be seen from the figure, the insulation structure with partial insulation extending 230 mm on both sides achieves the purpose of reducing heat flow, the temperature of outer surface is far below the critical point, and the thermal bridge can be completely eliminated. Thus the construction of partial extension insulation can achieve effective energy saving.

In order to obtain a more appropriate extended width \(B'\), the thermal performance of the structures with \(B' = 100\) mm, 150 mm, 200 mm and 115 mm which is half of the width of the area influenced, is investigated. The result is presented in Fig. 7b. The heat flux concentration at the boundary of the wall and the column decreases with the increase of \(B'\), while the temperature at the column remains almost the same. When \(B' = 115\) mm, the highest temperature of the thermal bridge is almost equal to the critical temperature. It can be considered that \(B' = 115\) mm has reached a relatively appropriate extended thermal insulation width. Therefore, the extended partial insulation structure need not cover the whole thermal bridge influence area, but only extend within half the width of the thermal bridge influence area, which can effectively break the thermal bridge.
The heat transfer coefficients of the walls with $t_2 = 68$ mm and with $t_2 = 40$ mm and $B' = 115$ mm, are $0.350 \text{ W/(m}^2\text{K)}$ and $0.354 \text{ W/(m}^2\text{K)}$, respectively. In consideration of the wall plaster, both meet the requirements of $0.350 \text{ W/(m}^2\text{K)}$. If the thermal bridge is eliminated totally, the thickness of the partial insulation without extension has to be about 100 mm. Compared with the structure with $t_2 = 40$ mm and $B' = 115$mm, the amount of material of the latter can be reduced by 34%, and the rectum distance of the column can be reduced by 60 mm and the occupied indoor building area can be decreased. Therefore, extending the partial insulation can meet the requirements of energy saving and eliminate the thermal bridge phenomenon.

![Figure 7. Influence of different configuration on external temperature of wall](image)

### 6. Discussion

In order to study the applicability and effectiveness of extending partial insulation, the heat transfer performance of the wall with different insulation materials and column forms is investigated.

#### 6.1. Thickness of insulation materials

Commonly insulation materials for exterior wall mainly include glass wool, plastic benzonic board (XPS), molded polystyrene board (EPS), rigid polyurethane, rock wool and so on. The thickness of aerated concrete block is still taken as 250mm. Under the requirement of the main wall heat transfer coefficient $0.35/(\text{m}^2\text{K})$, the thickness of external insulation can be calculated by Fourier one-dimensional heat transfer theory, as shown in Table 5.

| Materials       | Glass wool | Rock wool | XPS   | EPS   | Polyurethane |
|-----------------|------------|-----------|-------|-------|--------------|
| Heat conductivity / W/(m·K) | 0.040      | 0.044     | 0.036 | 0.041 | 0.0264       |
| Thickness /mm    | 60         | 65        | 55    | 60    | 40           |

#### 6.2. Thermal bridge influence zone of square steel tube column

The square steel tube commonly used in engineering are selected to conduct parameter analysis on the heat transfer performance of the wall adjacent to the steel tube. The temperature of the outer surface of the wall is shown in Fig. 8. It can be seen that the temperature is basically the same. The side length of the square steel tube ($b_c$) and the wall thickness ($t_c$) have little influence on the thermal bridge, which is similar to the analysis result of H-shaped steel column. The width of the thermal bridge influence area is stable around 260 mm.
6.3. Thickness and extension width of different insulation materials

Table 6 shows the optimal partial insulation thickness and extension width for the three column section forms. Five commonly used insulation materials are selected to be studied. According to the analysis method given above, the extension width is determined according to the principle that the outside surface temperature of the wall was all lower than the critical temperature.

| Material     | H-shaped column | Square steel tube column | CFST column |
|--------------|-----------------|--------------------------|-------------|
| Glass wool   | 40 / 115        | 45 / 130                 | 45 / 135    |
| Rock wool    | 45 / 125        | 50 / 135                 | 50 / 145    |
| XPS          | 35 / 110        | 40 / 120                 | 40 / 130    |
| EPS          | 40 / 135        | 45 / 150                 | 45 / 155    |
| Polyurethane | 25 / 115        | 30 / 130                 | 30 / 135    |

Note: 40 / 115 indicates the optimal partial insulation thickness and extension width.

7. Conclusion

(1) Thermal bridge appears at the position adjacent to the column in built-in composite insulation exterior wall of steel structure buildings without special insulation treatment. The heat flow increased by 55%, and heat transfer coefficient increases by 78%. Adding partial insulation at outside of column can improve the heat flux concentration, but there is still a thermal bridge at the boundary of the wall and column.

(2) The influence of thermal bridge at the junction of wall and column can be reduced by extending the partial insulation width outside the column, which has the advantages of reducing material cost and increasing usable area. For different insulation materials and column section types, the extension width of partial insulation as shown in Table 6 is suggested, which can meet the requirement of 75% energy saving in Beijing, and there will be no thermal bridge close to column.

(3) The heat transfer performance of the wall near the column is significantly affected by the form of the column section, but less affected by the size of the column section. Concrete-filled square steel tube column has the greatest influence on the heat transfer performance of the wall, while the thermal performance of H-shaped steel column is better.

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