EQUIVALENT SLABS APPROACH TO SIMULATE THE THERMAL PERFORMANCE OF THERMAL BRIDGES IN BUILDING CONSTRUCTIONS

Xie Xiaona, Jiang Yi

Department of Building Science and Technology, School of Architecture, Tsinghua University
Beijing 100084, China

ABSTRACT

In the paper, Equivalent Slabs approach is presented to compute thermal bridges in building constructions properly and quickly. The heat transfer of thermal bridges is decomposed into the heat transfer process influenced by outdoor temperature, indoor temperature and adjacent room temperature separately. 2+n (n is the number of adjacent rooms related to the thermal bridge) Equivalent Slabs are obtained to replace a thermal bridge to solve its 2+n heat transfer processes. The heat fluxes from Equivalent Slabs to room under unsteady boundary conditions are validated by Finite Difference Method. The results are simple and easy to be implemented into building energy simulation software. The computation time of such method is much shorter compared with existing methods.

KEY WORDS

Equivalent Slabs, heat transfer of thermal bridges, building thermal simulation

NOMENCLATURE

A_k —amplitude of the harmonic whose serial number is k, ℃

K_{1d} —the one-dimensional U-value of thermal bridge

K_{multi} —the multi-dimensional U-value of thermal bridge

l_r, λ_r, a_r —length, thermal conductivity and thermal diffusivity of layer r of Equivalent Slab

N —total number of scatter data

$q_{ad}(\tau)$ —heat flux in the time τ from the Equivalent Slabs of outdoor temperature and adjacent room temperature to room

T_k —period of the harmonic whose serial number is k, Hour

T_c —a period lies between 1 day period and the period of the inflexion in the heat flux curve, T_c is usually set as 100 hours depending on experience

α_k —phase of the harmonic whose serial number is k, Rad

τ —time，Hour

$\sigma'(\infty)$, $\sigma'(1\,day)$, $\sigma'(T_c)$ —heat flux from Equivalent Slab to room when the period is infinite value (steady), 1 day, and T_c separately

$\sigma(\infty)$, $\sigma(1\,day)$, $\sigma(T_c)$ —heat flux from thermal bridge when the period is infinite (steady), 1 day and T_c separately

INTRODUCTION

Generally, the heat transfer through building constructions is one-dimensional heat transfer when the dimension in the direction parallel to the surface is more than 10 times of that perpendicular to the surface. However, for actual building constructions, there are usually some columniations and girders in the junctions of different constructions, which is usually difficult to meet the above condition. The heat transfer through the zones near the junctions has to be treated as multi-dimensional heat transfer.

The local heat flux through thermal bridges is much greater than that through clear wall (the plat part of the wall that is uninterrupted by details) and thus more energy will have to be consumed to maintain comfortable building thermal environment. Research project RP-785 is carried out by ASHREA in 1997 (McGowan AG 1997). In the project, the heat transfer of thermal bridges is studied by experiment measurement and numerical simulation. A conclusion is drawn that U-values of thermal bridges are 22~49% higher than one-dimensional simplified results. The conclusion of Kosny (Kosny J and Kossecka E 2002) indicates that the clear wall comprises only 50~80% of the total area of the opaque wall. The remaining 20~50% area is thermal bridge area. Mao (Mao G and Johannesson G 1997) compared the simulating results when the heat transfer of thermal bridges is treated as two-dimensional heat transfer and one-dimensional heat transfer. The annual building energy increases 2~21%. The heat loss through building fabrics increases between 5~39%.

The software Heat2 (Blomberg T 1991) and Heat3 (Blomberg T 2000), which can be used for calculating the heat transfer of thermal bridges and developed by Lund University in Sweden and

Massachusetts Institute of Technology in USA, use an Explicit Finite Difference Method to calculate the heat transfer of thermal bridges under unsteady conditions. Heat2 is for two-dimensional heat transfer and Heat3 for three-dimensional case. Detailed local temperature field and heat flux can be calculated by the two software. However, Intensive computation time is necessary, for example, several hours is needed for two-dimensional heat transfer of a thermal bridge, which is too much to be applied in building energy simulation software because the computing time for one-dimensional fabric is less than 1 minute.

Deque (Deque F et al. 2001) and Gao (Gao Y et al. 2004) calculated heat transfer of thermal bridges using model size reduction techniques. Low-order model is easy to be implemented into building energy simulation software and has been adopted by EnergyPlus (Drury B et al. 2001), ESP-r (Clarke JA and McLean D 1988) and Clim2000 (Bonneau D et al. 1993). However, model size reduction techniques still consume much more computation time than clear wall, for example, about 1 hour is needed for two-dimensional heat transfer of a thermal bridge.

In previous study (Kosny J and Kossecka E 2002), response factors of thermal bridges are calculated by Finite Difference Method. The approach is ever used by DOE2 (Huang J et al. 1996). It demands 180~450 response factors to describe the thermal characteristic of a massive thermal bridge. A room usually has a lot of thermal bridges. Still, long computation time is needed to get the response factors. Too many response factors will make it troublesome using in building energy simulation software. “Thermally” equivalent wall concept is presented to be implemented in building energy simulation software replacing the response factors, which avoids the trouble but decreases computation precision at the same time.

The computing time for thermal bridges is much longer than that for clear wall using existing approaches. In the paper, Equivalent Slabs approach is therefore presented to solve the problem. The heat transfer of thermal bridges is decomposed into the heat transfer influenced by outdoor temperature, indoor temperature and adjacent room temperature separately. 2+n (n is the number of adjacent rooms related to the thermal bridge) Equivalent Slabs are calculated to replace a thermal bridge to solve its 2+n heat transfer processes. The heat flux from Equivalent Slabs to room under unsteady conditions is compared with that from the thermal bridge to room which is calculated by Finite Difference Method.

DECOMPOSITION OF THE HEAT TRANSFER OF A THERMAL BRIDGE

The boundary conditions of the heat transfer of a thermal bridge include outdoor temperature, indoor temperature and sometimes adjacent room temperature. The thermal bridges whose thermal characteristics don’t vary with boundary conditions are the object studied in the paper. The system of the kind of thermal bridges is linearity system and can be decomposed into several heat transfer processes influenced by different boundary conditions.

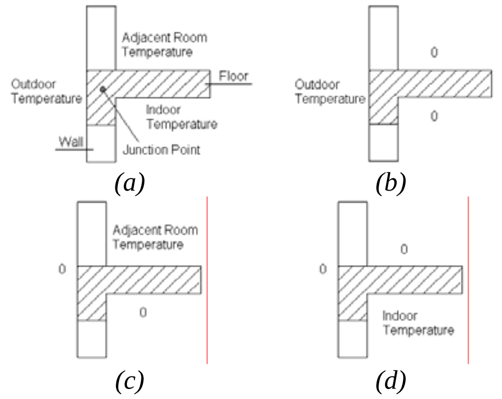


Figure 1 the schematic of the decomposition of a thermal bridge

Figure1 (a) shows a thermal bridge near the junction of a wall and a floor. When the section is far from the two points of the line where the wall joints the floor, the heat transfer of the thermal bridge can be regarded as two-dimensional heat transfer. In this study, two-dimensional thermal bridge is used to explain Equivalent Slabs approach and the approach can also be used in three-dimensional thermal bridge. The heat transfer of the thermal bridge which has one adjacent room can be decomposed into three heat transfer processes:

(1) Heat transfer process controlled by outdoor temperature. In the heat transfer process, indoor temperature and adjacent room temperature is set as zero, as shown in Figure 1(b).

(2) Heat transfer process controlled by adjacent room temperature. In the heat transfer process, outdoor temperature and indoor temperature is set as zero, as shown in Figure 1(c).

(3) Heat transfer process controlled by indoor temperature. In the heat transfer process, outdoor temperature and adjacent room temperature is set as zero, as shown in Figure 1(d).

ANALYSIS OF THE HEAT TRANSFER OF A THERMAL BRIDGE

Unsteady boundary conditions are important factors which make the heat transfer of thermal bridges complicated. In the engineering thermal calculation of building constructions, outdoor temperature, indoor temperature and adjacent room temperature are usually annual scatter data. Based on the theory of Fourier transform (Yan QS and Zhao QZ 1986), the annual scatter data can be obtained through summing some harmonics with difference periods and amplitudes. How to determine the periods and amplitudes of the harmonics are shown in the following first. And then how the heat flux through a thermal bridge to room varies with the periods is analyzed.

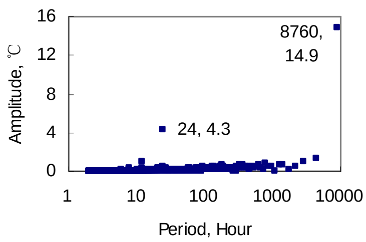
Fourier Analysis of Annual Temperature

Based on the theory of Fourier transform, the annual scatter data can be obtained by summing some harmonics with difference periods and amplitudes, as shown in Equation (1):

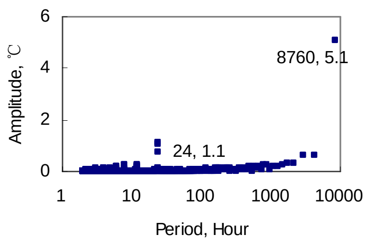
$$t_a = t_{a,m} + \sum_{k=1}^{N/2} A_k \sin(\frac{2\pi}{T_k}\tau + \alpha_k) \qquad (1)$$

Figure 2(a) shows the amplitude of the harmonics obtained by decomposing the outside temperature in Beijing China measured by China Meteorological Administration. The periods of the harmonics are following:

$$T_1 = 1\ year = 8760\ hour\ T_k = \frac{T_1}{k},\ k = 1:4380 \qquad (2)$$



(a) Outdoor temperature



(b) Indoor temperature

Figure 2 Amplitude of harmonics

Figure 2(a) indicates that the amplitude of 1 year period harmonic is highest, and the amplitude of 1 day period harmonic is the second. For indoor temperature, the amplitude of 1 year period harmonic and 1 day period harmonic is usually higher too, as shown in Figure 2(b). More detailed characteristic of indoor temperature is mainly determined by the control temperature of the HVAC equipment.

Analysis under Harmonic Conditions

In theory, the interface of a thermal bridge and clear wall should be far enough from the junction of different fabrics. In fact, the influence zone of a thermal bridge is finite. For the fabrics beyond the zone, the calculation error of one-dimensional heat flux is very small. To increase computation efficiency, proper interface should be determined. The principle to determine the interface is: look for the distance between the interface and the junction point, which is noted as b. For the calculation precision ε, when the distance is greater than b, the calculation error between one-dimensional result and multi-dimensional heat flux is required to be less than ε. It is to say that b is required to satisfy Equation (3):

$$\left| K_{multi} - K_{1d} \right|_{>b} < \varepsilon \qquad (3)$$

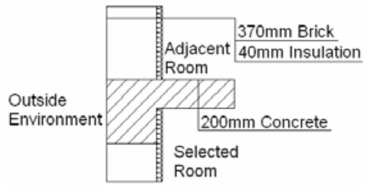


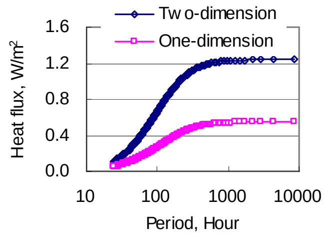
Figure 3 The thermal bridge near the junction of a wall and a floor

Figure 3 shows a thermal bridge near the junction of a wall and a floor. Table 1 shows the thermal parameters of materials in the wall and the floor.

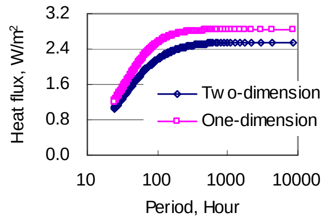
Table 1 Thermal parameters of materials

Material	Conductivity (W/m.℃)	Heat capacity (J/kg.℃)	Density (kg/m^3)
Brick	0.814	1800	879
Cement	0.93	1800	1050
Polystyrene	0.033	29	1791
Concrete	1.628	2500	837

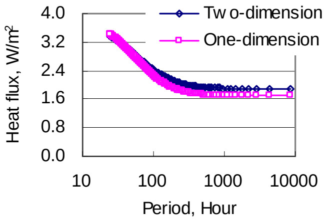
The two-dimensional heat flux amplitude from the thermal bridge to room is shown in Figure 4, which is compared to the one-dimensional simplified results.



(a) Outdoor temperature, amplitude is 1



(b) Adjacent room temperature, amplitude is 1



(c) Indoor temperature, amplitude is 1

Figure 4 Amplitude of heat flux from the thermal bridge to the room

Figure 4 shows the amplitude of the heat flux from the thermal bridge to room when outdoor temperature, adjacent room temperature and indoor temperature is harmonic with different periods. It can be seen from Figure 4(a) and (b) that the heat flux amplitude increases when the harmonic period becomes longer. It can be seen from Figure 4(c) that the heat flux amplitude decreases when the harmonic period becomes longer. When the period is long enough, the heat flux is inclined to steady state. It can also be seen from Figure 4 that the curve shape of two-dimensional heat flux is similar to that of one-dimensional results.

DETERMINATION OF EQUIVALENT SLABS

As analyze above, two-dimensional heat flux curve shape is similar to one-dimensional heat flux curve. Therefore, Equivalent Slabs are presented to replace the thermal bridge. Select three periods based on the heat flux curve shape. The heat flux from Equivalent Slabs to room is required to be equal to that from the thermal bridge to room for the selected harmonics. The heat flux from Equivalent Slab to room is required to satisfy Equation (4) and (5):

$$\sigma'(\infty) = \sigma(\infty) \tag{4}$$

$$\left|\sigma'(1\,day) - \sigma(1\,day)\right| + \left|\sigma'(T_c) - \sigma(T_c)\right| \text{ is minimum} \tag{5}$$

Equation (4) assures that the U-value of Equivalent Slab equals to that of thermal bridge. Equation (5) assures the difference between the heat flux from Equivalent Slab to room and that from thermal bridge to room minimum. T_c is a period lies between 1 day period and the period of the inflexion in the heat flux curve. It is usually set as 100 hours depending on experience, as shown in Figure 5.

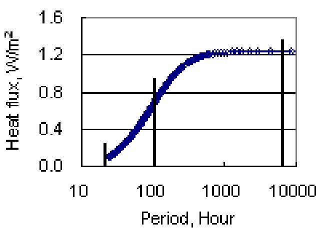
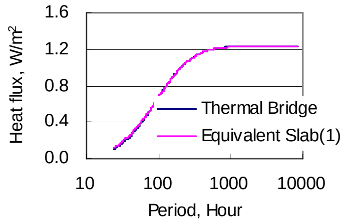
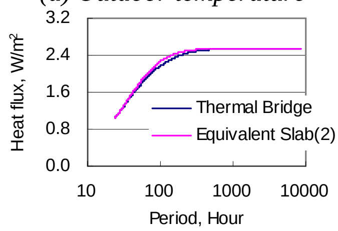


Figure 5 The three periods selected according to the curve shape of heat flux amplitude

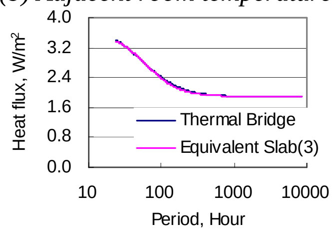
Through the two steps, the heat flux curve of Equivalent Slab is expect to be very close to that of thermal bridge, as shown in Figure 6. The calculation precision would be good enough when two layers are set in each Equivalent Slab.



(a) Outdoor temperature



(b) Adjacent room temperature



(c) Indoor temperature

Figure 6 Comparison of the heat flux between the Equivalent Slab and thermal bridge

The heat flux from Equivalent Slab to room can be expressed as:

$$\sigma(T_k) = f(T_k, l_r, \lambda_r, a_r) \tag{6}$$

More details about Equation (6) can be referenced in the book (Yan QS and Zhao QZ 1986). Solving Equation (4) ~ (6) and select proper material thickness in general scope, the thermal conductivity and thermal diffusivity of Equivalent Slab will be gotten.

VALIDATION BY DYNAMIC FDM PROGRAM

The calculation of each Equivalent slab is based on the heat flux from thermal bridge to room caused by three harmonic outside temperature, inside temperature or adjacent room temperature. The heat flux is calculated by Finite Difference Method without dispersing the time. The computing time is close to that of the steady heat transfer.

Dynamic Finite Difference Method program is used to validate the calculation precision of Equivalent Slabs. The grid of thermal bridges under unsteady conditions is set the same as that under harmonic conditions. The heat flux from thermal bridges to room and from Equivalent Slabs to room is compared under unsteady conditions.

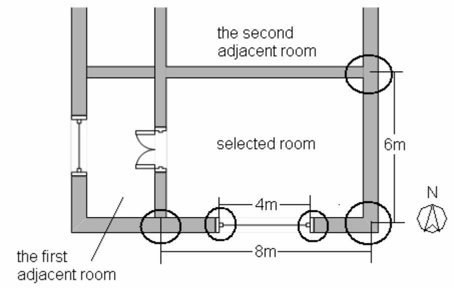
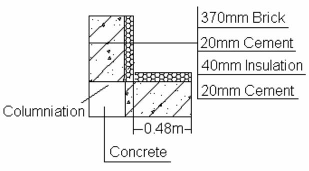
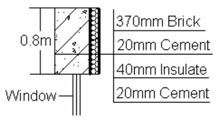


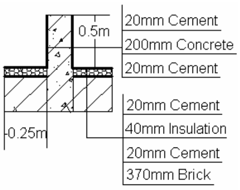
Figure 7 Thermal bridges in the cross section of a room



(a) Near the junction of exterior walls



(b) Near the junction of a wall and a window



(c) Near the junction of an exterior wall and an inner wall

Figure 8 The detailed main thermal bridges in the room

Figure 7 shows the plan section of a room and the thermal bridges in it. The detailed structures of the thermal bridges are shown in Figure 8. The thermal parameters of materials of exterior wall, inner wall and columniation are shown in Table 1. All thermal bridges in the room are treated as a big thermal bridge. The Equivalent Slabs of all boundary conditions are shown in Table 2.

Table 2 Materials of Equivalent Slabs

	Material	Thickness (mm)	Conductivity (W/m.℃)	Heat capacity(J/kg.℃)	Density(kg/m^3)
Outdoor temperature	Outside layer	100	0.127	1000	1.6
	Inside layer	100	0.298	1000	6050
Adjacent room temperature	Outside layer	100	1.111	1000	141
	Inside layer	100	0.383	1000	3548
Indoor temperature	Outside layer	100	0.727	1000	3327
	Inside layer	100	0.174	1000	1840

The "selected room" in Figure 7 is an office with HVAC equipment. The room temperature is controlled between 20~24℃. The "first adjacent room" is a corridor without HVAC equipment. The "second adjacent room" is a utility room without HVAC equipment. The annual hourly outdoor temperature, indoor temperature and adjacent room temperature are set as shown in Figure 9.

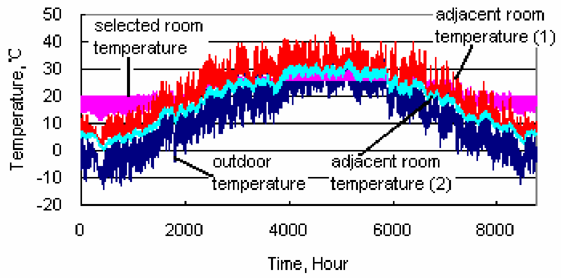
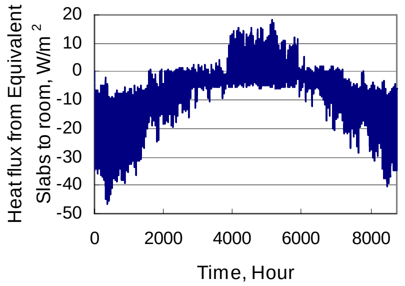
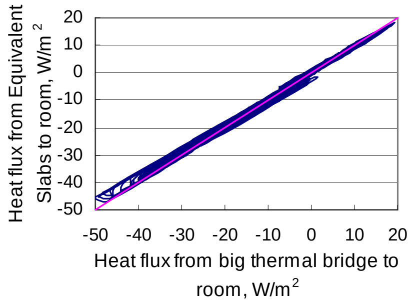


Figure 9 The annual hourly temperature

The heat flux from Equivalent Slabs to room under the set temperature is shown in Figure 10 (a). The comparison of heat flux from thermal bridges to room is shown in Figure 10 (b). It can be seen that the calculation precision of Equivalent Slabs is good.



(a) the heat flux from Equivalent Slabs to room



(b) comparison to the thermal bridges

Figure 10 the heat flux under unsteady boundary conditions

Implicit Difference Scheme is adopted in the dynamic FDM program. The time interval is 1 hour and the grid distance is 0.02 meter. In the same Pentium 4 computer, the computing time by dynamic FDM program is 132 minutes while the time by Equivalent Slabs approach is only 3 minutes. Moreover, when the values of boundary conditions are changed, it is not necessary to calculate the Equivalent Slabs again.

IMPLEMENTATION INTO BUILDING ENERGY SIMULATION SOFTWARE

Detailed Steps to Apply Equivalent Slabs Approach into Software

The Equivalent Slabs Approach can be implemented into building energy simulation software easily. The steps are following:

(1) Determine the thermal bridge zone in a room. The scope is firstly supposed to be large enough. Calculate the local U-value in different position of inner surface. If the difference between local U-value and one-dimensional fabric U-value is greater than permitted calculation error, the position is in the scope of thermal bridge;

(2) Treat all the thermal bridges in a room as a big thermal bridge and calculate the Equivalent Slabs of the big thermal bridge. Set boundary conditions of the big thermal bridge as harmonic with period: infinite, 100 hour and 1 day separately and compute the heat fluxes under the harmonic boundary conditions. And then calculate Equivalent Slabs based on the heat fluxes.

(3) Solving the heat transfer of the Equivalent Slabs for outdoor temperature and adjacent room temperature and obtain the heat flux from the Equivalent Slabs to room. Consider the heat flux as the heat source of room air, see Figure 11.

(4) Replace the thermal bridges with Equivalent Slab for indoor temperature, see Figure 11. Thus all the fabrics in the room are one-dimensional and easy to be computed.

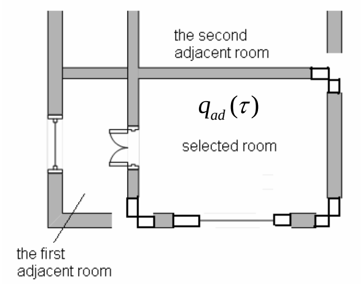


Figure 11 The thermal bridges are replaced with Equivalent Slab for indoor temperature

Following the steps above, the heat transfer of thermal bridges can be implemented into the building energy simulation software in which heat balance of a room is considered, for example, EnergyPlus (Drury B et al. 2001), ESP-r (Clarke JA and McLean D 1988), BLAST (Hittle DC 1979), DeST (Yan D and Jiang Y 2005), etc. The basic arithmetic of the software needs not to be changed.

Results of a demo case

An example is shown here for detail application. The shape of the building is shown in Figure 12. The used building energy simulation is DeST [15], which is developed by Tsinghua University, China.

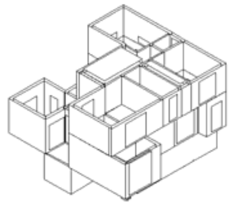


Figure 12 The plan of a building

The total energy for heating and cooling the rooms in the second floor is shown in Figure 13. The total energy for heating increases between 11% and 96% compared to one-dimensional results. The total energy for cooling increases between 2% and 13%.

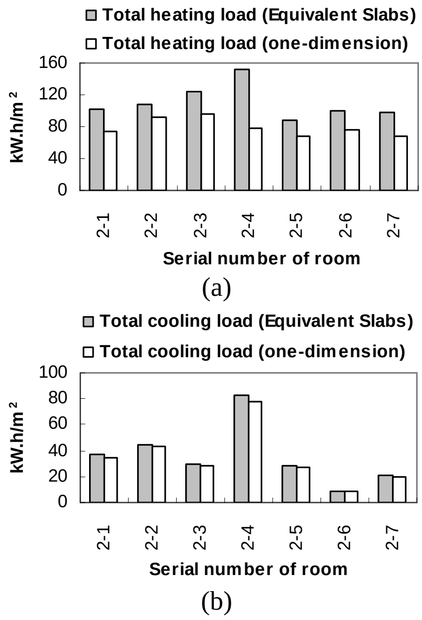


Figure 13 The annual total heating and cooling energy for some rooms in the building

CONCLUSION

In this study, a new approach is proposed for solving thermal bridge heat transfer. The following conclusion should be drawn:

(1) 2+n Equivalent Slabs are used to calculate the heat transfer of thermal bridges (n is the number of adjacent room). Each Equivalent Slab is presented to calculate the heat transfer of thermal bridges controlled by outdoor temperature, indoor temperature, or adjacent room temperature.

(2) The thermal bridges in a room are regarded as one big thermal bridge. The big thermal bridge is replaced by 2+n Equivalent Slabs. Thus the heat transfer of the fabric of the room can be treated as one-dimensional.

(3) The computing time for Equivalent Slabs is economic, which is only several minutes for two-dimensional heat transfer of a thermal bridge. Each Equivalent Slab is obtained based on the heat flux controlled by harmonic with

three periods. The computing time for heat flux controlled by harmonic is close to steady heat flux.

(4) The computing precision of Equivalent Slabs is good. The heat flux from Equivalent Slabs to room is compared with that from thermal bridges to room under harmonic and unsteady boundary conditions. They meet each other well.

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