Evaluation of anchor bolts on the thermal performance of building insulation materials

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Abstracts

For Near-zero-energy buildings, the application of building insulation materials is widely used. Anchor bolts, as a fixing element of insulators, were applied to increase the safety of insulators, however, due to their high thermal conductivity they would cause point thermal bridge and lead to an obviously negative effect on the insulation function of building envelopes. However, very few studies have systematically explored this issuer. This study, therefore, proposed a prediction approach with a 3D model developed by MATLAB to investigate the effect of anchors on thermal performance of building envelopes with insulation layers fixed by anchors. It also provides a new indicator, namely, equivalent effective thermal conductivity of the insulators, which can be used in many popular building energy prediction packages. Simulation results revealed that it is a complicated thermal impact of anchor bolts on an external building envelope, which would be affected by many parameters of different envelope contents. For example, glass fiber insulation materials with aluminum alloy anchor bolts, the effective thermal conductivity would rise up to 0.6946 W/(m·K), with an 18 times rise; and the corresponding envelope thermal transmittance would increase by 33%. This novel model would provide an accurate and easy method to evaluate the thermal effect of anchor bolts, and it is applicable to anchors made of any materials. The proposed method could be a reference in energy performance prediction for high-performance buildings.

Keywords: Near-zero-energy buildings; thermal conductivity; anchor bolts; thermal insulation materials.

1. Introduction

The energy demand for cooling and heating buildings is increasing greatly, especially in developing countries [1]. According to existing literatures, buildings can contribute to up to 40% of the whole energy consumption of our society [1-2]. Many studies have shown that promoting thermal performance of building envelopes, especially external walls, can significantly decrease buildings' energy demand [3-5]. Near-zero-energy buildings (NZEBs) refer to those buildings with high energy performance. In China, the government is currently very supportive on developing such buildings, which have high requirement on average thermal transmittance of external walls [6-7]. Therefore, when estimating the performance of NZEBs, an accurate calculation of thermal transmittance of external walls becomes extremely important.

When calculating thermal transmittance, thermal bridge is one major influential factor resulting in higher heat transfer coefficient. Due to existence of thermal bridge, the amount of undesirable heat loss or gain could rise significantly because of large heat flux at the edges of different materials, due to changed thermal conductivity from one material to another, especially when there are metal materials, such as window frames [8-9]. One previous study has revealed that the overall effect from thermal bridge on energy use of buildings could go up to 35% [10].

Due to the above reason, in recent years, thermal bridge has captured great attentions from researchers, and many studies have carried out to evaluate the impact of different thermal bridges caused by building components, such as doors, windows, balcony, pillars and beams [11-19]. For example, Asdrubali [11] has proposed an easy method of indicating factors causing linear thermal bridges in buildings and has given specific effective percentage on unwanted thermal transmittance of building walls. Baba [15] suggested the importance of focusing on building connection points to avoid generation of thermal bridges. Most existing literatures, however, only concerned the effect from linear thermal bridges caused by components like balcony connections and floor supports, neglecting the impact from point thermal bridges. This neglection may lead to an underestimated building energy consumption. It is important to note, therefore, that besides linear thermal bridges, point thermal bridges caused by components like anchor bolts crossing thermal insulation layers should also be considered when estimating the performance of NZEBs.

Normal wall construction with insulation systems generally consists of a bearing layer (foundation wall), an insulation layer (insulation product) plus supporting elements. Anchor bolts, as one major supporting element, are used for keeping insulation layers onto bearing layers [20], to enhance safety of insulation layers. However, due to its higher heat conductivity comparing to insulation materials, it often brings undesirable heat transfer, working as point thermal bridges [21]. Therefore, it is highly required to evaluate the impact of anchor bolts on thermal performance of building external envelopes.

Many studies have explored the impact of thermal bridges in building applications. However, very few has systematically explored thermal bridges caused by anchors used in insulation layers of external building envelopes, especially for building performance simulation. For example, ISO 6946 introduces a method calculating the total thermal resistance of a building component consisting of both homogeneous and inhomogeneous layers. However, it has indicated that this method is not applicable for cases where insulation is bridged by metal materials, such as metal fasteners (anchors). It means that when the thermal conductivity between materials is very different, the calculation results of the simple method in the standard ISO 6946 will not be accurate enough.

To fill this gap of research, this study has proposed a new model considering the effect of anchors on thermal performance of building envelopes with insulation layers fixed by anchors. The model is applicable to anchors made of any materials. It also provides a new indicator, namely, equivalent effective thermal conductivity of insulators, which can be used in many popular building energy prediction packages. Using the new model, influential factors on point thermal bridges, such as thermal and dimension properties of different envelope contents, have been systematically investigated in the study. This novel model introduced here provides an accurate and easy method to evaluate the effect of anchor bolts in energy performance prediction for high-performance buildings.

2. Simulation Approach

In this study, three models have been proposed in MATLAB: Model 1 showed one benchmark envelope with one bearing layer and one insulation layer only, i.e. without anchor bolts, as shown in Figure 1a; Model 2 reflected actual conditions with anchor bolts to fix insulation layers onto bearing layers, as shown in Figure 1b, and Model 3 was an equivalent model, without any anchor bolt but the same thermal transmittance as Model 2, as shown in Figure 1c.

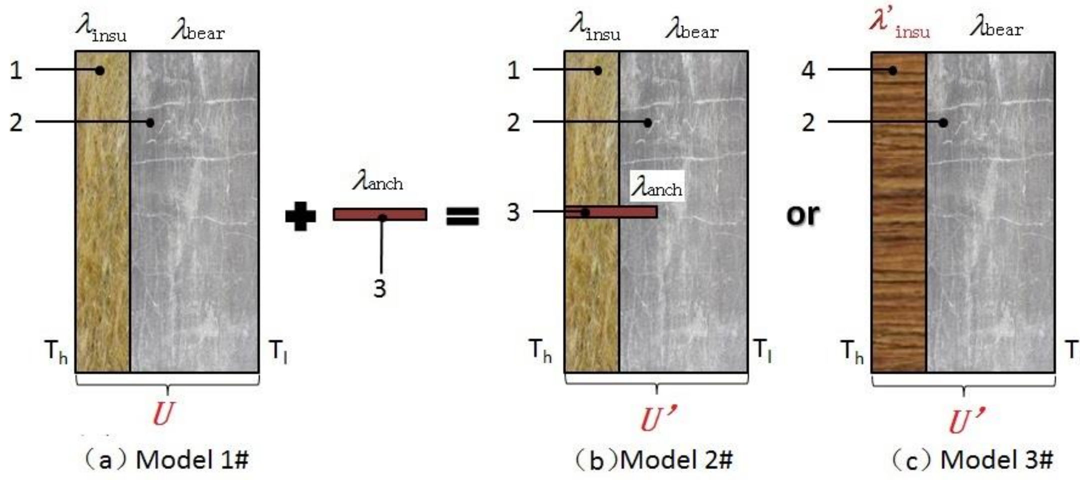


Figure 1: Three models proposed for the study: (a) benchmark envelope without anchor bolts; (b) actual envelope with anchor bolts; (c) equivalent envelope with the same thermal transmittance as Model 2.

1- insulation layer; 2- bearing layer; 3- anchor bolt; 4- imaginary insulation layer.

2.1 Simulation method and process

According to previously published work by the authors [22-24], a 3D model developed in MATLAB was applied to predict the heat performances of all three scenarios defined in Figure 1, with only heat conduction through building envelopes was considered.

Firstly, the building envelope was assumed as being rectangle, as shown in Figure 1. Then, a grid of X×Y×Z was used for this model, with increments of dx, dy, and dz. Here, $Xdx=Ydy$, i.e. the spacing of anchor bolts of 100mm, which meet the standard requirement of anchor bolts installation [25], while Zdz equaled to the overall thickness including both bearing layers and insulation layers. The final model had a grid of

50×50×40~190 and a unit size of 2 mm, balancing both prediction accuracy and calculation time.

Secondly, according to the location and size of each part (bearing layer, insulation layer, anchor bolt) in the building envelope, as shown in Figure 1a and 1b, the value of each thermal phase unit was endowed, i.e. *Condt*=ones (X, Y, Z). Besides, a temperature matrix, *Temp*=ones (X, Y, Z), was used for the equation solution.

Thirdly, as defined in Equation (1), a steady-state energy equation for 3D heat transfer was established as control equations, where T was temperature, λ_x, λ_y, and λ_z were material conductivities in each direction, respectively.

$$\frac{\partial}{\partial x}(\lambda_x \frac{\partial \mathrm{T}}{\partial \mathrm{x}}) + \frac{\partial}{\partial y}(\lambda_y \frac{\partial \mathrm{T}}{\partial \mathrm{y}}) + \frac{\partial}{\partial z}(\lambda_z \frac{\partial \mathrm{T}}{\partial \mathrm{z}}) = 0 \tag{1}$$

Because the sum of heat flow through each unit equaled to zero, for each calculation unit (*i, j, k*), the model control equation was written as Equation (2), where each q represented heat flows going in and going out of the unit (*i, j, k*) in different directions, in W. Specifically, Figure 2 shows the heat flow $q_{(i-1,j,k)}$ on the contact surfaces of unit (*i-1, j, k*) and unit (*i, j, k*), which can be determined by Equation (3), where, T was the temperatures of these two units, in K; $\lambda_{(i-1/2,j,k)}$ was the effective thermal conductivity between these two units, in W/(m·K), which can be calculated by Equation (4).

$$q_{(i-1,j,k)} - q_{(i+1,j,k)} + q_{(i,j-1,k)} - q_{(i,j+1,k)} + q_{(i,j,k-1)} - q_{(i,j,k+1)} = 0 \tag{2}$$

$$q_{(i\text{-}1,j,k)} = \lambda_{(i\text{-}1/2,j,k)} \times (dy \times dz) \times (T_{(i\text{-}1,j,k)} - T_{(i,j,k)}) / dx \tag{3}$$

$$\lambda_{(i-1/2,j,k)} = 2\frac{Condt_{(i-1,j,k)} \cdot Condt_{(i,j,k)}}{Condt_{(i-1,j,k)} + Condt_{(i,j,k)}} \tag{4}$$

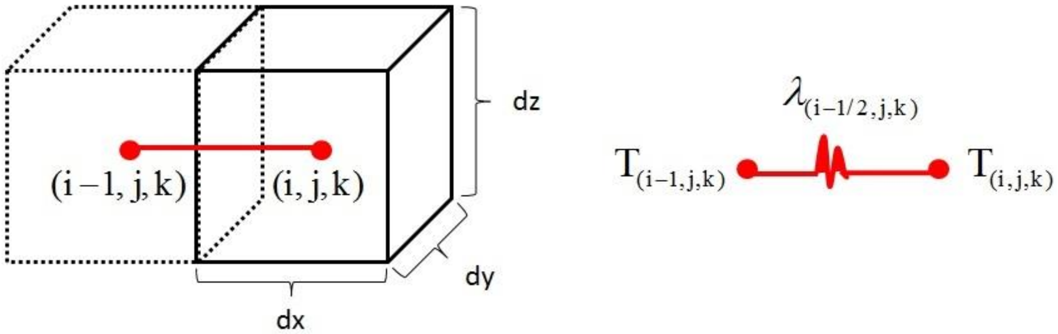


Figure 2: Computational units (*i-1, j, k*) and (*i, j, k*).

Fourthly, the boundary conditions were defined as followings. For the two surfaces in the envelope thickness direction (z-direction), the temperatures were set as known functions due to inside and outside air temperature, i.e. T_o=36°C and T_i=26°C, respectively. The other four sides were insulated, which is attributed to the spacing between anchor bolts is sufficient and there is no thermal effect between each two anchor bolts.

Finally, the convergence standard was defined as Equation (5), where *P* represented the number of iterations.

$$\left(\frac{\sum_{i,j,k}(T^{P+1}_{(i,j,k)} - T^{P}_{(i,j,k)})^2}{\mathrm{X}\times\mathrm{Y}\times\mathrm{Z}}\right)^{\frac{1}{2}} < 2\times10^{-4} \tag{5}$$

Moreover, in order to verify the model's accuracy, two calculation results were compared as follows. Specifically, in Figure 1a, no anchor bolt was inserted in the envelope, and it only consisted of one insulation layer and one bearing layer, hence equal to a simple series model. Therefore, here the accuracy of the new proposed model could be got by comparing two group values of thermal conductivities λ_e of the whole envelope. Firstly, for the series model, λ_e could be calculated by Equation 9. Secondly, the calculated λ_e the proposed model could be got by our model. Figure 3 has depicted a good agreement between the two sets of λ_e curves (R-square=0.92) to confirm the accuracy of the model. Besides this, in our previous studies [22-24], the model's accuracy has been experimentally validated as well.

$$\lambda_e = \frac{L_{insu} + L_{bear}}{L_{insu} / \lambda_{insu} + L_{bear} / \lambda_{bear}} \tag{9}$$

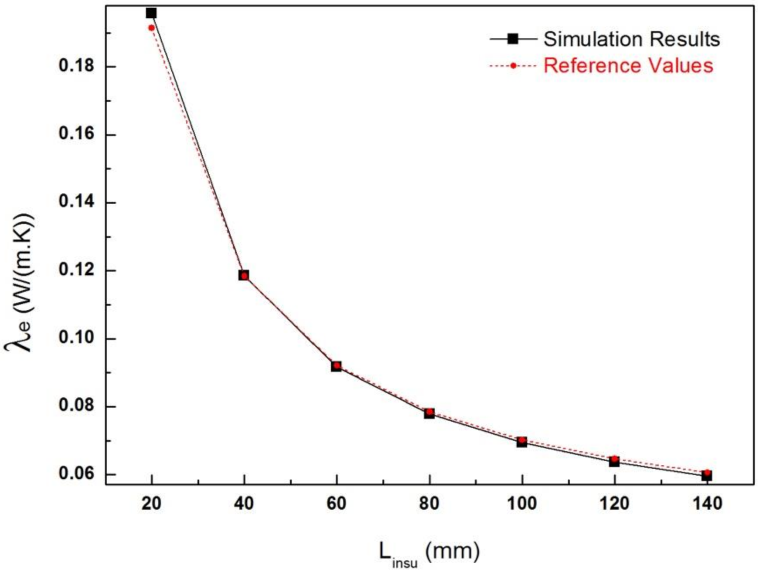


Figure 3: Effective thermal conductivities calculated by this simulation model and a series model.

However, there are also some limitations in this model. As we knew, the anchor bolt is assumed to be a rectangular strip but is actually cylindrical. But, in this envelope system, the thermal effect caused by anchors was the point heat bridge, so the specific shape of the anchor bolt can be ignored.

2.2 Indicators used to evaluate the impact from anchor bolts

In this study, to identify anchor bolts' effect, two indicators, i.e. point thermal transmittance X (W/K) and a new thermal conductivity of the equivalent insulation layer λ'_{insu} (W/(m·K)), were applied.

In practice, anchor bolts are penetrated in local areas of insulation layers, like point thermal bridges. Therefore, it can be evaluated by point thermal transmittance [26]. Here, X was defined as the difference between two specific heat losses, as determined by Equation 6, where, H and H' were the specific heat losses caused by identical envelope surface areas without and with anchor bolts, respectively, in W/K; Q and Q' were heat losses caused by identical envelope surface areas without and with anchor bolts, respectively, in W, and T_h and T_l were high and low temperatures of envelope surfaces, respectively, in K.

$$X = H' - H = Q - Q' / (T_h - T_l) \tag{6}$$

As shown in Figures 1a and 1b, the major difference between Model 1 and Model 2 was whether anchor bolts were embedded into building envelopes, resulting in overall thermal transmittances of U and U', respectively. According to ISO 6946 [27], U' can be calculated by Equation 7, where, $\triangle U$ is the transmittance correction factor, in W/(m^2·K).

$$U' = U + \Delta U \tag{7}$$

In Equation 7, if more than one anchor bolt was repetitively embedded into building envelopes, ΔU could be determined by Equation 8, where, X was point thermal transmittance, in W/K, and N was anchor bolt density, i.e. the number of anchor bolts per square meter of the envelope, in m^{-2}.

$$\Delta U = X \cdot N \tag{8}$$

When calculating building energy consumption using traditional simulation packages, such as TArch and EnergyPlus, the effect from anchor bolts is often neglected so there is no available model inputs given to this problem. In this study, Model 3 (Figure 1c) with an imaginary insulation layer was developed to solve this problem, and Model 3 had the same overall thermal transmittance, i.e. U', as Model 2 (Figure 1b). In Model 3, the equivalent thermal conductivity of the imaginary insulation layer was defined as λ'_{insu}, and it could be obtained by Equation 9, where, λ_{bear} was the bearing layer' conductivity, in W/(m·K), and L_{insu} and L_{bear} were the thicknesses of both insulation and bearing layers, respectively, in m.

$$\lambda'_{insu} = \frac{U'\lambda_{\mathrm{bear}}\ L_{\mathrm{insu}}}{\lambda_{\mathrm{bear}} - U'L_{bear}} \tag{9}$$

2.3 Simulation parameters

X and λ'_{insu} will be affected by both thermal conductivity and structural parameters of three items in the envelope, namely, anchor bolts, insulation layers and bearing layers. The thermal conductivities of different items are listed in Table 1.

Table 1: Thermal conductivities of anchor bolt, insulation layer and bearing layer used for the simulation (W/(m·K)).

Anchor bolt	Plastic	Stainless steel	Steel	Aluminum alloy
λ_{anch}	0.27	27.6	40.2	160
Insulation layer	Polyurethane foam	Glass fiber	Wool fiber	Foam ceramic
λ_{insu}	0.023	0.036	0.06	0.11
Bearing layer	Autoclaved aerated concrete	Hollow block	Solid masonry	Ordinary reinforced concrete
λ_{bear}	0.23	0.58	1.16	1.4

For anchor bolts, materials commonly used in engineering applications were selected, such as plastic, stainless steel, steel and aluminum alloy. For the insulation layer, polyurethane foam, glass fiber, wool fiber and foam ceramic were used, and for the bearing layer, autoclaved aerated concrete, hollow block, solid masonry, and ordinary reinforced concrete were chosen, according to literatures [28-31].

According to the requirements and installation of anchor bolts for thermal insulation of external walls [25], structural parameters were set as followings:

Anchor bolts:

The cross-sectional area (*A*) was defined as 100mm^2, 196mm^2, 324mm^2 and 484mm^2, i.e the anchors with the diameters of 10mm, 16mm, 18mm, 22mm, respectively. Insert depth (*D*) into the bearing layer was considered due to its big impact on the stability and heat properties of building envelopes. In this study, *D* was set between 20mm and 70mm, incrementing every 10mm. In addition, density of anchor bolts (*N*) was defined as the number of anchor bolts per 1m^2, including 1, 3, 4, 5, 7, 9, 11, 25, 30, 40, 60, 80 and 100 /m^2, respectively. According to industry-standard [32], in engineering applications, commonly used densities of anchors were 4, 5, 9, and 11 /m^2.

Insulation layer and bearing layer:

L_{insu} and L_{bear} were used to represent the thickness of the insulation and bearing layers, respectively. L_{insu} was changing from 20mm to 140mm, with an increment of 20mm. L_{bear} was chosen according to common wall thickness, including 60mm, 100mm, 120mm, 180mm and 240mm.

For the base case model, important parameters were defined as λ_{anch}=160W/(m·K), λ_{insu} =0.036W/(m·K), λ_{bear}=1.4W/(m·K), A=100mm^2, D=30mm, N=100m^{-2}, L_{insu}=40mm and L_{bear}=100mm.

3. Simulation Results

Before carrying out the simulation, the results calculated by the methods presented in ISO6946 and our numerical simulation were compared. Here, the base case model was used except N=4m^{-2}, and different anchor materials were applied for comparing. The final comparison was showed in Figure 4.

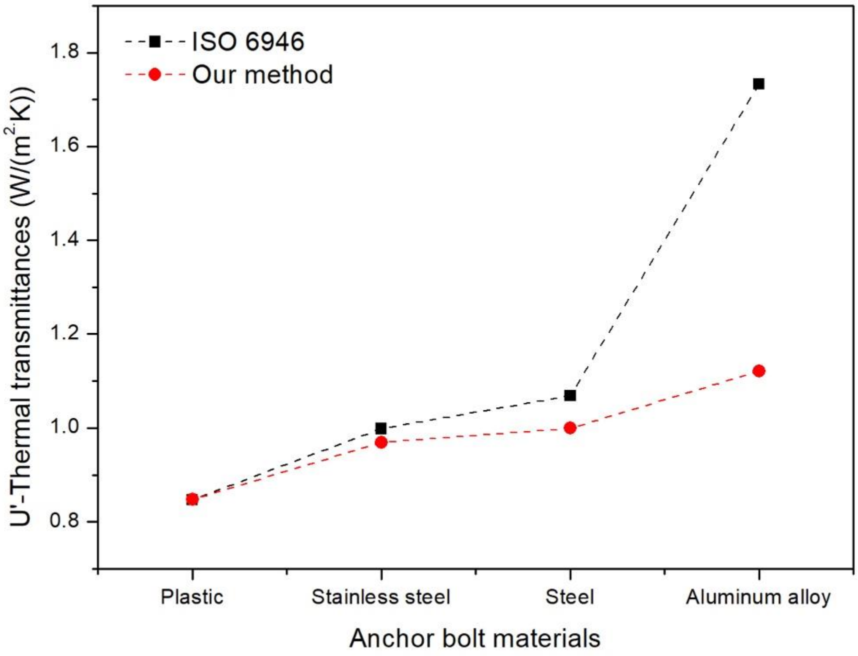


Figure 4: Comparison between the methods presented in ISO6946 and our model.

It can be found that there are small differences between these two methods, but when the thermal conductivity of anchor bolt increases high up to 160 W/(m·K) there is an big difference (for aluminum alloy). This is consistent with the notes proposed in the standard ISO 6946, that is, when the thermal conductivity between materials is very different, the calculation results of the simple method in the standard will not be accurate enough. This is because as the thermal conductivity of the anchor bolt increases, the thermal bridge effect produced by it will become more obvious, and it will cause the heat transfer between different material components. Therefore, final heat transfer results cannot be accurately obtained only through the simple series-parallel method and the correction of the empirical formula.

3.1 Effect from thermal properties of different envelope contents

3.1.1 The effect of anchor bolts

Figure 5 depicts the changes of both the point thermal transmittance X and the imaginary insulation layer thermal conductivity λ'_{insu} to the change of anchor bolt thermal conductivity λ_{anch}. It indicates that both X and λ'_{insu} increase with the increase of λ_{anch}. Particularly, when λ_{anch} increased from 0.27 to 160 W/(m·K), with a rise of X from 0.0005 to 0.0689 W/K. The blue curve shows that with a rise of λ_{anch}, λ'_{insu} increased from 0.039 to 0.695 W/(m·K), by about 18 times.

In summary, the thermal property of anchor bolts has a huge effect on the whole envelope's thermal performance, reflecting the high importance of selecting suitable anchor bolts.

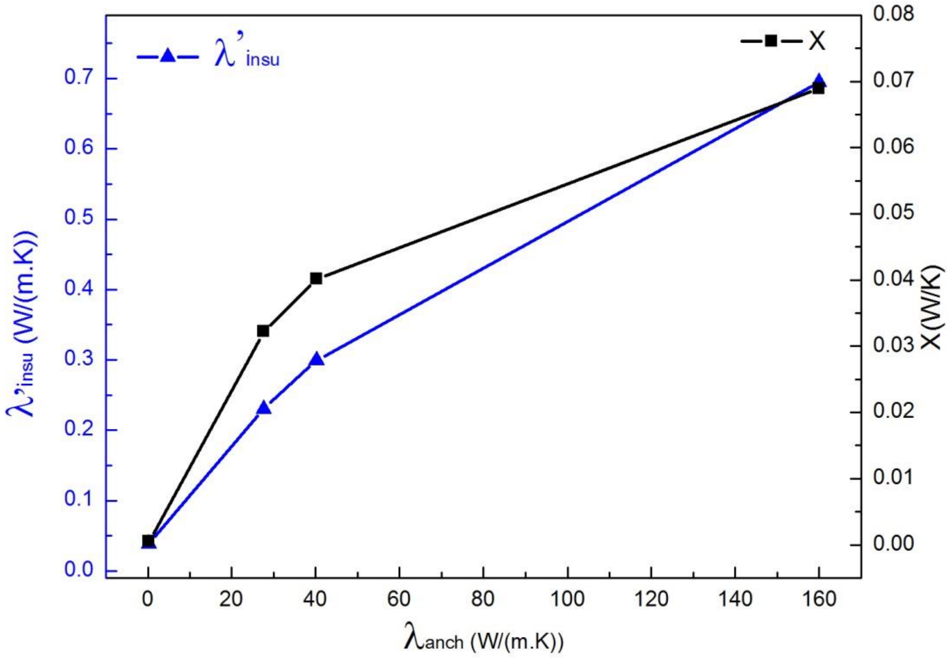


Figure 5: Change of both point thermal transmittance X and imaginary insulation layer thermal conductivity λ'_{insu} to the change of anchor bolt thermal conductivity λ_{anch}.

3.1.2 The effect of the insulation layer

Figure 6 shows the variation of *X* and λ'_{insu} caused by λ_{insu} of the insulation layer. These curves indicate that with the increase of λ_{insu}, λ'_{insu} increases, while *X* decreases. Specifically, when λ_{insu} is increased from 0.023 to 0.110 W/(m·K), λ'_{insu} will change from 0.674 to 0.824 W/(m·K), but with a drop of *X* from 0.072 to 0.06 W/K. So the corresponding effect rate of the anchor bolt on the whole envelope *U* will decrease from 14 to 2.8 times. It can be included that, with the increase of λ_{insu}, the anchor bolt's influence becomes unapparent. This phenomenon illustrates that the anchor bolt's thermal impact on the whole envelope is more pronounced for the insulation layer with a small thermal conductivity than that with large thermal conductivity.

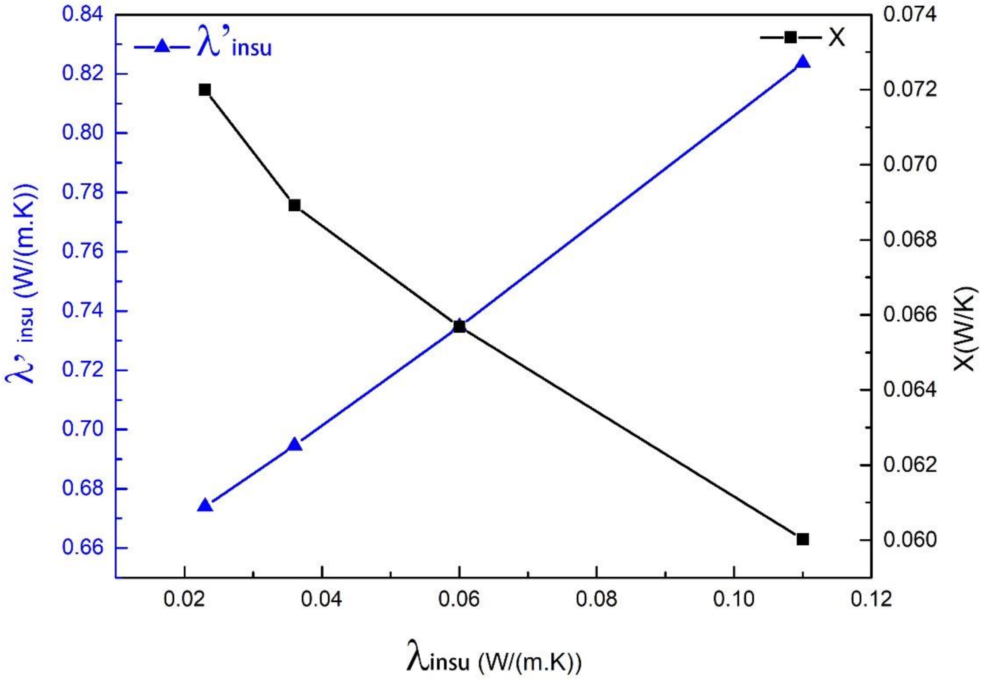


Figure 6: The variation of point thermal transmittance *X* and the imaginary insulation

layer equivalent thermal conductivity λ'_{insu} with the change of the insulation layer thermal conductivity λ_{insu}.

3.1.3 The effect of the bearing layer

Figure 7 illustrates that both X and λ'_{insu} increase with the increase of λ_{bear}. To be specific, the chart shows that when λ_{bear} changes from 0.23 to 1.40 W/(m·K), λ'_{insu} grows from 0.350 to 0.655 W/(m·K), with the increase of 9 to 18 times. Moreover, X of 0.012 W/K rises to 0.069 W/K, and the impact rate on thermal transmittance will rise up to 8 times. Therefore, when estimating the effect of anchor bolts, the choice of bearing layer material also needs to be considered.

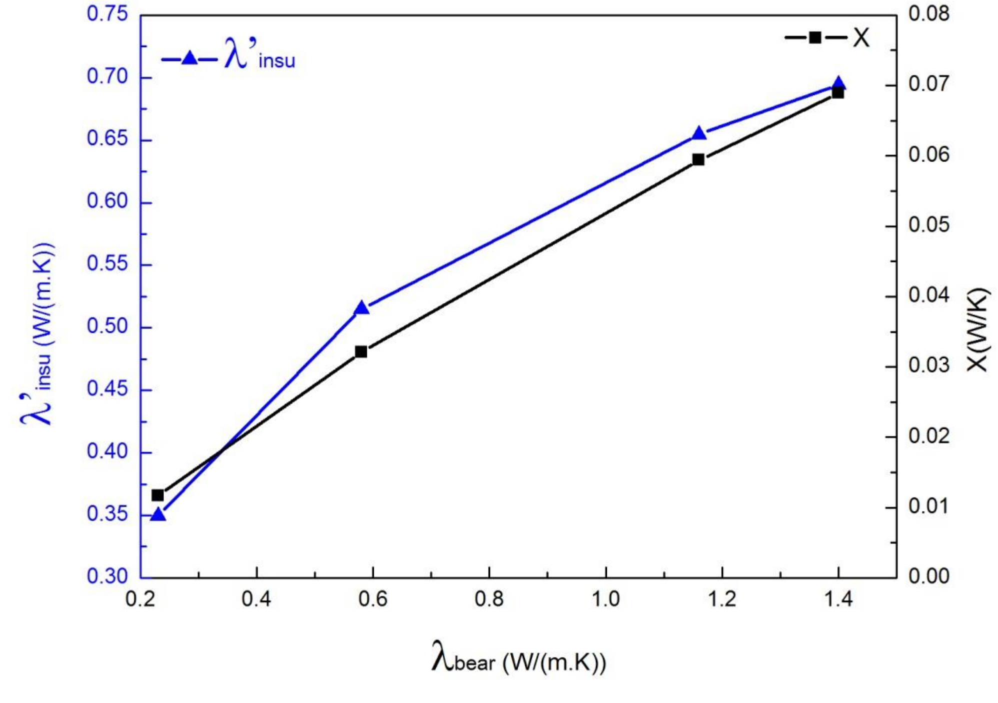


Figure 7: The variation of point thermal transmittance X and the imaginary insulation layer thermal conductivity λ'_{insu} with the change of the bearing layer thermal

conductivity λ_{bear}.

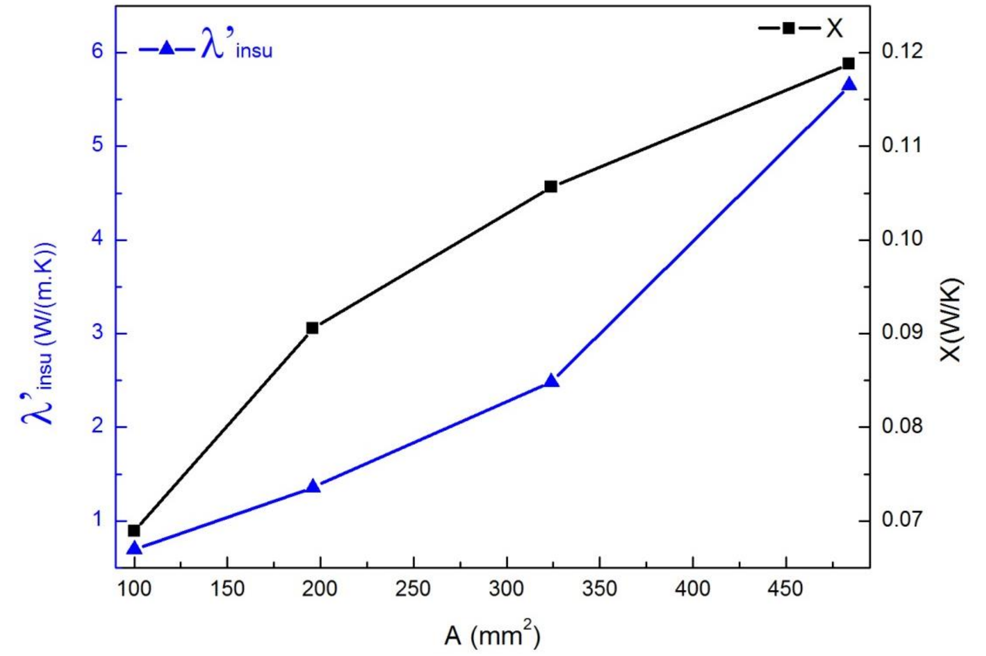
In conclusion, for λ'_{insu}, thermal conductivities of all envelope contents (anchor bolts, the insulation layer, and the bearing layer) have a positive effect, i.e. they will cause the rise of λ'_{insu}. While, for X, both anchor bolts and the bearing layer have positive effects, while the insulation layer has a negative effect. That is to say, that point thermal bridge caused by anchor bolts is more remarkable especially for the application of insulation layer with a smaller thermal conductivity.

3.2 Effect form structure parameters of different envelope contents

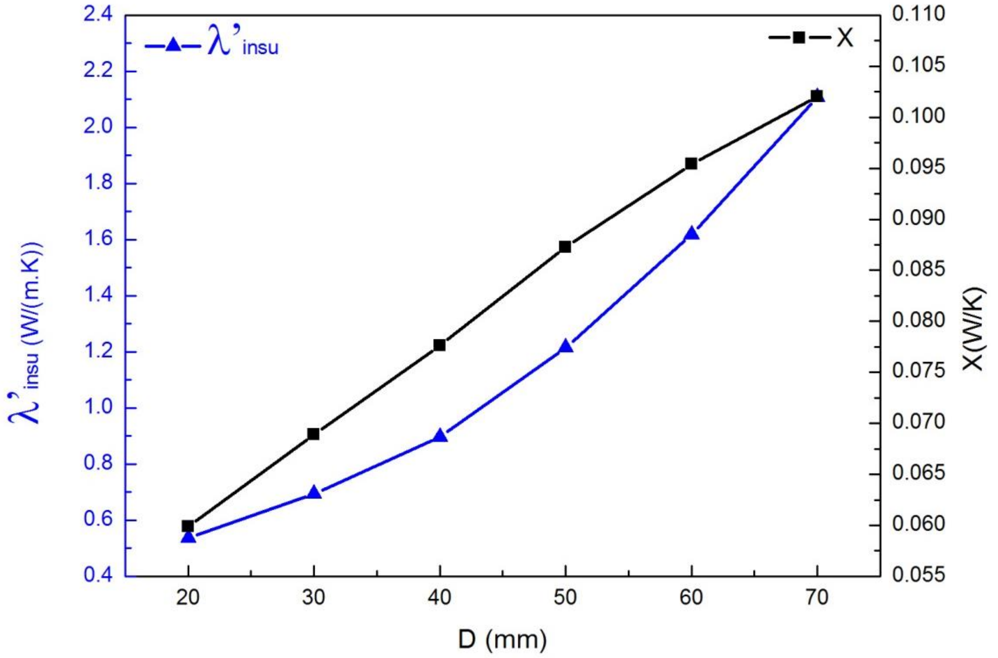
3.2.1 The effect of anchor bolts

Figure 8a and 8b show that the influences of cross-sectional area A and insert depth D of anchor bolts on X and λ'_{insu}, and it can be seen that these two influence trends are similar. Both X and λ'_{insu} increase with the increase of A and D.

Firstly, Figure 8a indicates that when A increases from 100 to 484 mm^2 (the diameter from 10mm to 22mm), X and λ'_{insu} increase from 0.069 to 0.119 W/K and from 0.695 to 5.649 W/(m·K), respectively. Secondly, Figure 8b indicates the impact of D on X and λ'_{insu}. And it can be seen that with the increase of D from 20 to 70 mm, X and λ'_{insu} rise from 0.060 to 0.102 W/K and from 0.695 to 2.108 W/(m·K), respectively. It can be concluded that although the larger size of the anchor bolts will make the stronger of its fixation, it causes the greater impact of the heat bridge.



(a) The effect of the cross-sectional area (*A*).



(b) The effect of the insert depth (*D*).

Figure 8: The variation of point thermal transmittance X and the imaginary insulation layer thermal conductivity λ'_{insu} with the changes of the cross-sectional area (A) and insert depth (D) of anchor bolts.

Figure 9 illustrates that the effect of the anchor bolt density *N*. Firstly, λ'_{insu} grows with an *N* rise. For example, when *N* increases from 1 to 100 m^{-2}, λ'_{insu} grows from 0.039 to 0.688 W/(m·K), with a corresponding rise of 7 to 1811 times. While in our model, the effect of each anchor bolt is not interacting, so *X* remains the same with the increase of *N*, equaling to 0.069 W/K.

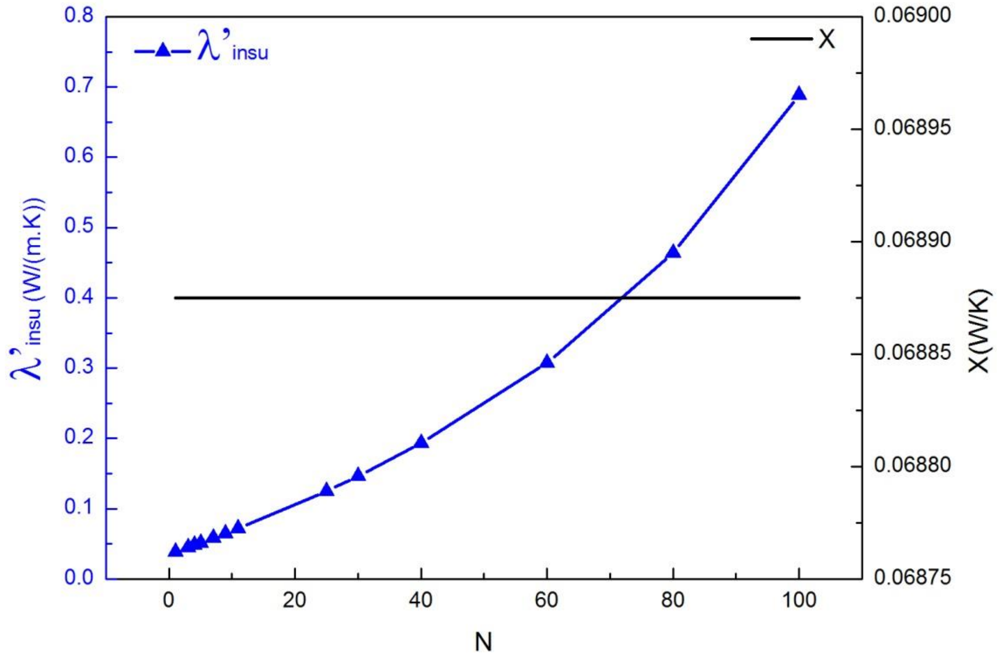


Figure 9: The variation of point thermal transmittance *X* and the imaginary insulation layer thermal conductivity λ'_{insu} with the change of anchor bolt density (*N*).

In conclusion, both of the cross-sectional area *A* and insert depth *D* of anchor bolts have a side influence on *X* and λ'_{insu}, while the density of anchors *N* would only increase the side effect of anchors on λ'_{insu}. Therefore, in practical applications, under the premise of fully considering the anchoring effect, the size and amount of the anchor should be reduced as much as possible, thereby reducing the negative impact on the heat insulation of the insulator.

3.2.2 The effect of insulation layer's thickness

From Figure 10, two curves of X and λ'_{insu} show opposite trends. Firstly, the blue curve indicates that the increasing insulation layer's thickness L_{insu} causes the increase of λ'_{insu}, which is attributed to the effect of anchor bolts. As we know, when L_{insu} is increased, the corresponding length of the adopted anchor bolt increases, resulting in an increase of λ'_{insu}. Specifically, when L_{insu} is increased from 20 to 140 mm, λ'_{insu} will be increased from 0.465 to 1.303 W/(m·K), with a corresponding increasing rate from 1192 to 3518 times. It is interesting to note that for the insulator with L_{insu} of 80mm, the effect rate by anchors on both λ'_{insu} and X turn to slow, which is because that the increase in L_{insu} will bring two changes, one is that the insulation effect of the insulator is increased, and the other is that the heat bridge effect caused by the increase of the corresponding length of the anchor is increased. And these two changes will lead to totally different results in the heat transfer through the whole envelopes. When the L_{insu} is short, the effect by anchors leads roles, while with the increase of L_{insu} (L_{insu}>80mm), the effect by the insulator increases and will more counteract some of the side effects of the anchor. Therefore, Figure 10 also shows that with the rise of L_{insu}, X drops from 0.071 to 0.053 W/K, and the drop rate becomes more obvious when L_{insu} is higher than 80mm, which illustrates that the L_{insu} rise can weaken the effect of anchor bolt on the heat transfer of the whole envelope.

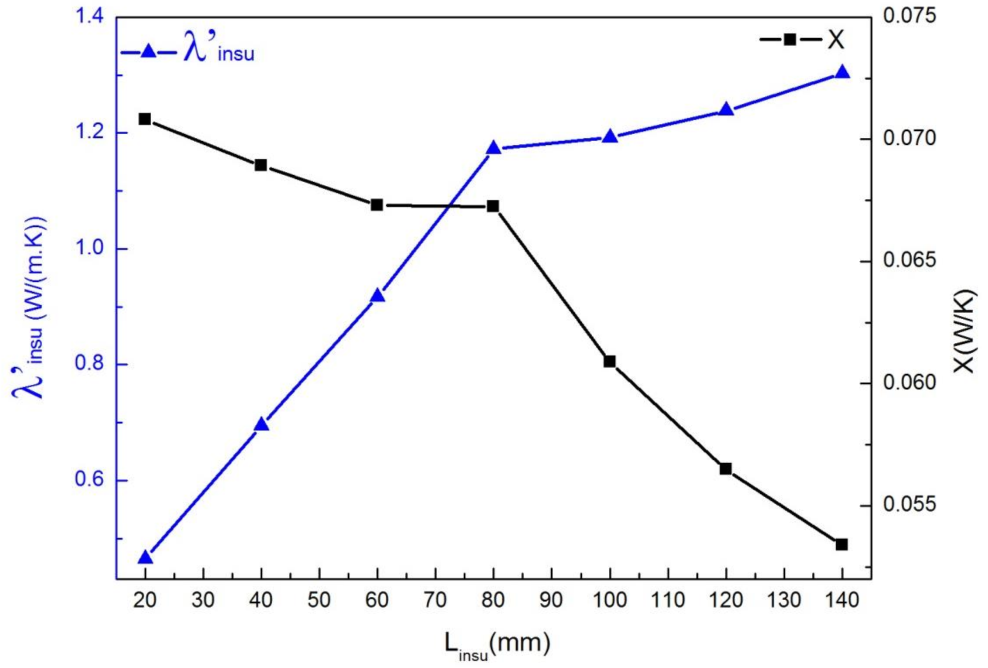


Figure 10: The variation of point thermal transmittance *X* and the imaginary insulation layer thermal conductivity λ'_{insu} with the change of insulation layer thickness L_{insu}.

3.2.3 The effect of bearing layer's thickness

From Figure 11, two curves show similar trends, i.e., both of *X* and λ'_{insu} decline with the increase of bearing layer's thickness L_{bear}. Specifically, when L_{bear} is increased from 60 to 240 mm, *X* and λ'_{insu} will be decreased from 0.096 to 0.044 W/K and from 0.767 to 0.588 W/(m·K), respectively.

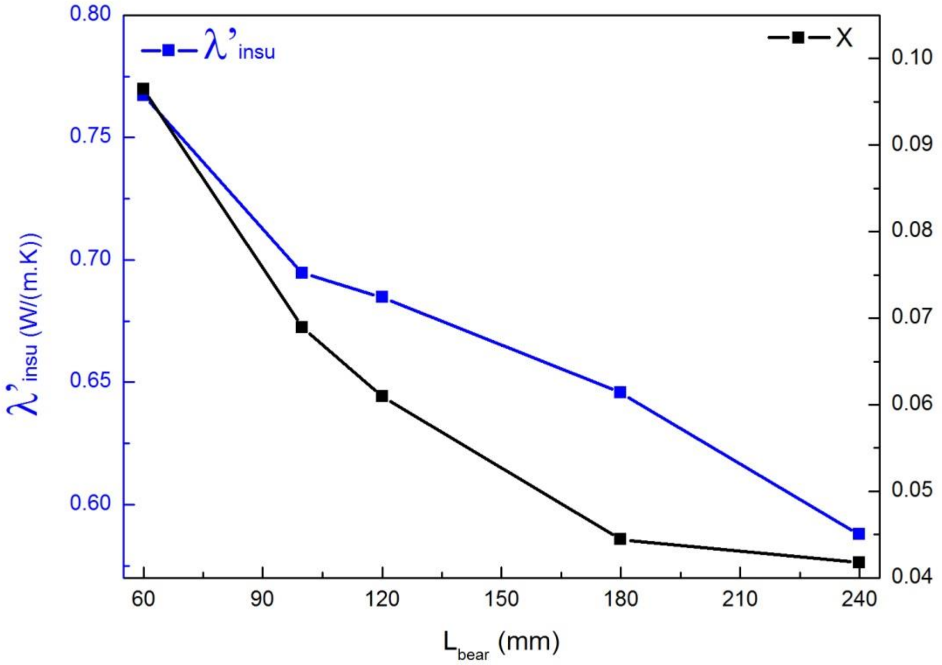
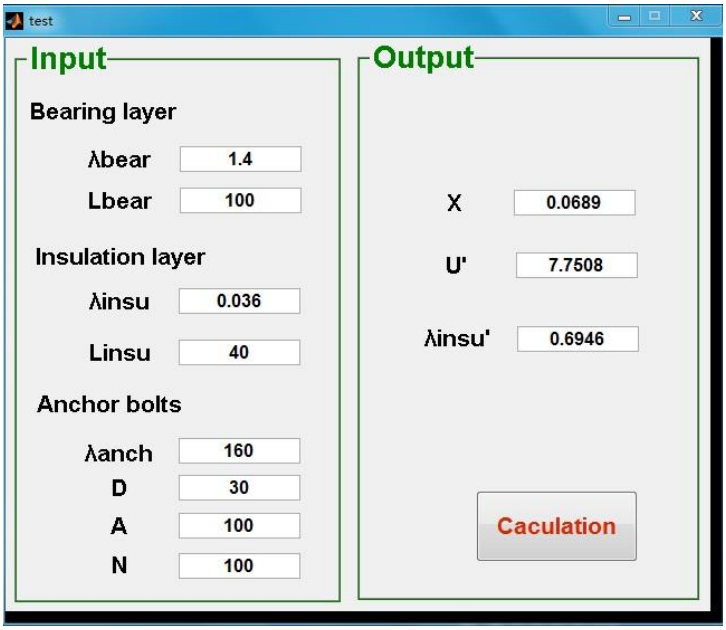


Figure 11: The variation of point thermal transmittance and the imaginary insulation layer thermal conductivity with the change of bearing layer thickness.

In conclusion, for anchor bolts， the large size and more application density will cause the increase of λ'_{insu} and X. While, for the bearing layer, a thicker bearing layer results in both decreases of λ'_{insu} and X. For the insulation layer, the thicker insulation layer leads to an increase of λ'_{insu}, but a decrease of X.

4 Discussion: the visual interface application

The above simulation results indicate that the thermal performance of external building envelope with anchor bolts is a complex question, which is affected by many parameters of different envelope contents, including bearing layer, insulation layer, and anchor bolts. Therefore, for the convenience of the processing, this paper further gave a visual interface (Figure 12), which can be regarded as a reference for practitioners to evaluating the thermal effect of anchor bolts on building energy calculation. Using this visual interface, practitioners only need input relevant parameters of envelopes, then the output (X, U', and λ'_{insu}) will be calculated by our model.



Bearing layer
λbear 1.4
Lbear 100
Insulation layer
λinsu 0.036
Linsu 40
Anchor bolts
λanch 160
D 30
A 100
N 100

X 0.0689
U' 7.7508
λinsu' 0.6946

Figure 12: The calculation interface for evaluating the effect of anchor bolts.

Finally, take an envelope with anchor bolts as an example. As showed in Figure 12， inputs relevant parameters of envelope (Bearing layer: λ_{bear} =1.4 W/(m·K), L_{bear}=100 mm; Insulation layer: λ_{insu} =0.036 W/(m·K), L_{insu}= 40 mm; Anchor bolts: λ_{anch} =160 W/(m·K), D=30 mm, A=100 mm^2, N=4 m^{-2}.), then the output results (X=0.0689 W/K, U'=7.7508 W/(m^2·K), and λ'_{insu} =0.6946 W/(m·K)) can be calculated. It can be found that compared to the original insulation layer (λ_{insu}=0.036 W/(m·K)), the corresponding λ'_{insu} rises up to 0.6946 W/(m·K), with an 18 times rise. While comparing to an envelope without anchor bolts, the application of anchor bolts increases its thermal transmittance by 33%. It can be seen that the application of anchor bolts has a big side impact on the thermal insulation system. The existence of anchor bolts will increase the effective thermal conductivity of thermal insulation systems and increase the unwanted heat transfer of buildings.

5. Conclusions

In this paper, a simple prediction approach for evaluating the thermal performance of external building envelopes with anchor bolts has been introduced. Simulation results revealed that it is a complicated thermal impact of anchor bolts on an external building envelope, affected by many parameters of different envelope contents.

- For anchor bolts, increasing λ_{anch}, A, D and N would all result in increases of λ'_{insu} and X. For example, in the base case model, replacing plastic anchors by aluminum anchors would further increase the λ'_{insu} by 18 times.
- For the insulation layer, both increases of λ_{insu} and L_{insu} would lead to an increase of λ'_{insu}, but a decrease of X. For insulators with high λ_{insu} anchor influences would become unapparent, for example, replacing the polyurethane foam by the foam ceramic, the growth multiple of λ'_{insu} will reduce from 29 to 7.5 times.
- For the bearing layer, an increase of λ_{bear} would cause increases of both λ'_{insu} and X, but a thicker L_{bear} resulted in decreases of λ'_{insu} and X. For example, in the base case model ordinary reinforced concrete would lead to λ'_{insu} growth by high up to18 times.

Besides, a practical visual interface was developed, which could be used by practitioners for evaluating the thermal effect (X, U', and λ'_{insu}) of anchor bolts on building energy predictions.

In conclusion, for the design of high-energy performance buildings, the impact of anchor bolts on building's thermal performance is not negligible, and the approach introduced in this paper provides a simple and quick way to evaluate this effect.

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References

[1] Palacios-Munoz B, Gracia-Villa L, Zabalza-Bribián I, et al. Simplified structural design and LCA of reinforced concrete beams strengthening techniques[J]. Engineering Structures, 2018, 174:418-432.

[2] Hossain M F. Design and construction of ultra-relativistic collision PV panel and its application into building sector to mitigate total energy demand[J]. Journal of Building Engineering, 2017, 9: 147-154.

[3] Vincelas F F C, Ghislain T, Robert T. Influence of the types of fuel and building material on energy savings into building in tropical region of Cameroon[J]. Applied Thermal Engineering, 2017, 122.

[4] Jazaeri J, Gordon R L, Alpcan T. Influence of building envelopes, climates, and occupancy patterns on residential HVAC demand[J]. Journal of Building Engineering, 2019, 22: 33-47.

[5] Ji, R., Zheng, Y., Zou, Z., Chen, Z., Wei, S., Jin, X., & Zhang, M. Utilization of mineral wool waste and waste glass for synthesis of foam glass at low temperature [J]. Construction and Building Materials. 2019, 215:623-632.

[6] Harkouss F, Fardoun F, Biwole P H. Multi-objective optimization methodology for net zero energy buildings[J]. Journal of Building Engineering, 2018, 16: 57-71.

[7] Vassallo D, Follesa M, Fragiacomo M. Seismic design of a six-storey CLT building in Italy[J]. Engineering Structures, 2018, 175:322-338.

[8] Tenpierik M, Cauberg H. Analytical Models for Calculating Thermal Bridge Effects Caused by Thin High Barrier Envelopes around Vacuum Insulation Panels[J]. Journal of Building Physics, 2007, 30(3):185-215.

[9] Larbi A B, Couchaux M, Bouchair A. Thermal and mechanical analysis of thermal break with end-plate for attached steel structures[J]. Engineering Structures, 2017, 131:362-379.

[10] J. Šadauskiene, Ramanauskas J, L. Šeduikyte, et al. A Simplified Methodology for Evaluating the Impact of Point Thermal Bridges on the High-Energy Performance of a Passive House[J]. Sustainability, 2015, 7(12):16687-16702.

[11] Asdrubali F, Baldinelli G, Bianchi F. A quantitative methodology to evaluate

thermal bridges in buildings[J]. Applied Energy, 2012, 97: 365-373.

[12] Song J H, Lim J H, Song S Y. Evaluation of alternatives for reducing thermal bridges in metal panel curtain wall systems[J]. Energy and Buildings, 2016, 127:138-158.

[13] Bedon C, Amadio C. Enhancement of the seismic performance of multi-storey buildings by means of dissipative glazing curtain walls[J]. Engineering Structures, 2017, 152:320-334.

[14] Ascione F, Bianco N, Masi R F D, et al. Design of the Building Envelope: A Novel Multi-Objective Approach for the Optimization of Energy Performance and Thermal Comfort[J]. Sustainability, 2015, 7(8):10809-10836.

[15] Baba F, Ge H. Dynamic effect of balcony thermal bridges on the energy performance of a high-rise residential building in Canada [J]. Energy and Buildings, 2016, 116:78-88.

[16] Oh J M, Song J H, Lim J H, et al. Analysis of Building Energy Savings Potential for Metal Panel Curtain Wall Building by Reducing Thermal Bridges at Joints Between Panels ☆[J]. Energy Procedia, 2016, 96:696-709.

[17] Julye R D F, Eduardo G D C. Thermal bridges modeling in South Brazil climate: Three different approaches [J]. Energy and Buildings, 2018, 169:271-282.

[18] Gomes A P, Souza H A D, Tribess A. Impact of thermal bridging on the performance of buildings using Light Steel Framing in Brazil[J]. Applied Thermal

Engineering, 2013, 52(1):84-89.

[19] Bergero S, Cavalletti P, Chiari A. Energy refurbishment in existing buildings: thermal bridge correction according to DM 26/06/2015 limit values [J]. Energy Procedia, 2017, 140:127-140.

[20] Pisareva N V, Kulaenko S I , Tsypin S Y . Development of ceramic anchors for installing fibrous heat insulation[J]. Refractories, 1991, 32(7-8):411-413.

[21] Fukuyo K. Heat flow visualization for thermal bridge problems[J]. International Journal of Refrigeration, 2003, 26(5):614-617.

[22] Ji R, Zhang Z, He Y, et al. Simulating the effects of anchors on the thermal performance of building insulation systems[J]. Energy & Buildings, 2017, 140:501-507.

[23] Ji R, Zhang Z, Liu L, et al. Development of the random simulation model for estimating the effective thermal conductivity of insulation materials[J]. Building & Environment, 2014, 80(80):221-227.

[24] Ji R, Zhang Z, He Y, et al. Synthesis, characterization and modeling of new building insulation material using ceramic polishing waste residue[J]. Construction & Building Materials, 2015, 85:119-126.

[25] Biru Zhang. Design, requirements and installation of anchor bolts for external thermal insulation of external walls [J]. Construction technology. 2013(11):49-50. (in Chinese)

[26] The International Organization for Standardization (ISO 10211). Thermal Bridges

in Building Construction—Heat Flows and Surface Temperatures–Detailed Calculations; The International Organization for Standardization (ISO): Geneva, Switzerland, 2007.

[27] The International Organization for Standardization (ISO 6946). Building Components and Building Elements-Thermal Resistance and Thermal Transmittance-Calculation Method; The International Organization for Standardization (ISO): Geneva, Switzerland, 2007.

[28] Jarfelt, Ulf, and O. Ramnas. "Thermal conductivity of polyurethane foam-best performance." 10th International Symposium on district heating and cooling. Chalmers University of Technology Goteborg, Sweden, 2006.

[29] Ji R, Wu S, Yan C, et al. Preparation and Characterization of the One-piece Wall Ceramic Board by Using Solid Wastes[J]. Ceramics International, 2017.

[30] Qingfang Ma. (1986). The manual of practical thermophysical properties. The press of China's agricultural machinery. (in Chinese)

[31] Qiu L, Zou H, Tang D, et al. Inhomogeneity in pore size appreciably lowering thermal conductivity for porous thermal insulators[J]. Applied Thermal Engineering, 2017, 130:1004-1011.

[32] Ministry of Housing and Urban-Rural Development of the People's Republic of China. JG/T366-2012 Anchor for external wall insulation [S]. Beijing: China Standard Press

Table and Figure Captions

Table 1: Thermal conductivities of anchor bolt, insulation layer and bearing layer used for the simulation (W/(m·K)).

Figure 1: Three models proposed for the study: (a) benchmark envelope without anchor bolts; (b) actual envelope with anchor bolts; (c) equivalent envelope with the same thermal transmittance as Model 2. 1- insulation layer; 2- bearing layer; 3- anchor bolt; 4- imaginary insulation layer.

Figure 2: Computational units ($i-1, j, k$) and (i, j, k).

Figure 3: Effective thermal conductivity calcualted by this simulation model and a series model.

Figure 4: Comparison between the methods presented in ISO6946 and our model.

Figure 5: Change of both point thermal transmittance X and imaginary insulation layer thermal conductivity λ'_{insu} to the change of anchor bolt thermal conductivity λ_{anch}.

Figure 6: The variation of point thermal transmittance X and the imaginary insulation layer equivalent thermal conductivity λ'_{insu} with the change of the insulation layer thermal conductivity λ_{insu}.

Figure 7: The variation of point thermal transmittance X and the imaginary insulation layer thermal conductivity λ'_{insu} with the change of the bearing layer thermal conductivity λ_{bear}.

Figure 8: The variation of point thermal transmittance X and the imaginary insulation

layer thermal conductivity λ'_{insu} with the changes of the cross-sectional area (A) and insert depth (D) of anchor bolts.

Figure 9: The variation of point thermal transmittance X and the imaginary insulation layer thermal conductivity λ'_{insu} with the change of anchor bolt density (N).

Figure 10: The variation of point thermal transmittance X and the imaginary insulation layer thermal conductivity λ'_{insu} with the change of insulation layer thickness L_{insu}.

Figure 11: The variation of point thermal transmittance X and the effective insulation layer thermal conductivity λ'_{insu} with the change of bearing layer thickness L_{bear}.

Figure 12: The calculation interface for evaluating the effect of anchor bolts.