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Thermal Bridge Effects in Prefabricated Buildings and Their Impact on Indoor Thermal Environment

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ABSTRACT

With the advancement of industrialized and modular construction, prefabricated buildings have become a significant trend in the construction industry due to their efficiency, eco-friendliness, and sustainability. However, thermal bridge effects are inevitable in the structural design of prefabricated buildings, adversely impacting energy performance and indoor thermal conditions. Thermal bridges cause uneven heat transfer between the building's interior and exterior, increasing energy consumption and affecting indoor temperature and humidity levels. Investigating the thermal bridge effects and their influence on the indoor thermal environment is crucial for enhancing energy efficiency and optimizing building design. Current research methods primarily rely on finite element analysis and heat conduction equations to assess thermal bridges, but these methods often overlook dynamic factors, limiting their accuracy and applicability in real-world scenarios. This paper first explores the formation mechanisms of thermal bridges and their specific impacts on the thermal environment in prefabricated buildings, analyzing the contributions of different structural components to thermal bridging and establishing corresponding heat conduction models. Subsequently, a heat conduction differential equation and boundary conditions for the temperature field in prefabricated buildings are constructed. By combining numerical simulations with experimental validation, this study analyzes the impact patterns of thermal bridges under varying thermal conditions. Through these investigations, the paper aims to provide theoretical guidance for the design of prefabricated buildings and offer scientific support for policy development, promoting further advancements in energy efficiency and indoor comfort in prefabricated construction.

1. INTRODUCTION

Prefabricated buildings, as a new type of building form, have been widely applied in recent years due to their characteristics of efficiency, eco-friendliness, and sustainability [1-4]. With the progress of building industrialization and modularization, prefabricated buildings have gradually become an important trend in the global construction industry [5, 6]. However, due to the characteristics of prefabricated buildings in production, transportation, assembly, and other stages [7], thermal bridge effects are inevitably present in their structural design [8, 9]. Thermal bridge effects not only affect the energy performance of buildings [10] but also have a significant impact on the indoor thermal environment [11], thereby influencing occupants' comfort and the building's energy consumption. Investigating the thermal bridge effects in prefabricated buildings and their impact on the indoor thermal environment is of great significance for improving the energy efficiency of prefabricated buildings and optimizing building design.

The thermal bridge effects in prefabricated buildings are not only a major challenge in the study of building thermal environments but also an important entry point for achieving building energy-saving goals. Thermal bridge effects lead to uneven heat transfer between the building's interior and exterior [12], increasing the building's energy consumption and affecting indoor temperature and humidity levels [13]. Understanding thermal bridge effects and their impact on the thermal environment can provide a theoretical basis for optimizing building structural design and improving building energy efficiency [14, 15]. Therefore, studying the thermal bridge effects in prefabricated buildings not only helps enhance the accuracy of building design but also provides scientific support for developing more efficient and comfortable living environments.

At present, research on thermal bridge effects mainly focuses on traditional buildings [16-19], whereas systematic studies on thermal bridge effects in prefabricated buildings and their impact on the indoor thermal environment are relatively scarce. Alghamdi et al. [10] used finite element analysis and heat conduction equations to evaluate the impact of thermal bridge effects on building energy consumption. However, this method tends to overly rely on static models, neglecting the influence of dynamic factors. Although the method in Reference [20] can reveal the location and intensity of thermal bridge effects in buildings, it insufficiently considers the thermal conduction characteristics at joints in prefabricated buildings and their real-time impact on the indoor thermal environment under different seasons and climate conditions. The limitations of these methods in practical applications affect their accuracy and applicability.

This paper mainly focuses on studying the thermal bridge effects in prefabricated buildings and their impact on the indoor thermal environment. First, it explores the formation mechanisms of thermal bridge effects and their specific impacts on the thermal environment in prefabricated buildings, analyzes the contributions of different structural components to thermal bridge effects, and establishes corresponding heat conduction models. Subsequently, this paper constructs heat conduction differential equations and boundary conditions for the temperature field in prefabricated buildings. Through a combination of numerical simulations and experimental verification, the impact patterns of thermal bridge effects under different temperature fields are analyzed. Through these studies, this paper not only provides theoretical guidance for the design of prefabricated buildings but also offers a basis for the formulation of relevant policies, promoting further development in the energy efficiency and comfort of prefabricated buildings.

2. THERMAL BRIDGE EFFECTS IN PREFABRICATED BUILDINGS AND THEIR IMPACT ON INDOOR THERMAL ENVIRONMENT

2.1 Heat conduction

In prefabricated buildings, the heat conduction process mainly refers to the phenomenon where heat is transferred through molecular thermal motion in building materials or structural components due to the presence of a temperature difference. Prefabricated buildings are usually composed of multiple prefabricated parts, such as walls, roofs, and floors. These components are connected through fasteners to form the structural system. Due to differences in thermal conductivity between materials of different components and the presence of seams or joints, these connection points often become "weak spots" for heat transfer, resulting in the so-called thermal bridge effect. Under the influence of the temperature gradient, heat is quickly transferred through these "thermal bridges," leading to uneven temperature distribution inside the building, thereby affecting the indoor thermal environment. The thermal bridge effect reduces the energy efficiency of the building, increases heating and cooling loads, and leads to higher energy consumption. Additionally, due to the uneven temperature field, local overheating or overcooling may occur, affecting the comfort of the occupants.

Let the temperature s be a function of spatial coordinates a, b, c, and time π, then the expression for the two-dimensional steady-state temperature field is:

$$s = d\left(a,b,c,\pi\right) \tag{1}$$

The impact of heat conduction on the indoor thermal environment in prefabricated buildings mainly manifests in the uneven temperature distribution caused by the thermal bridge effect. Since prefabricated buildings are made up of multiple prefabricated components, connection points often serve as the key paths for heat transfer. The thermal conductivity at these joints is relatively high, making thermal bridge phenomena easy to form. When the external environment temperature is low or high, heat will transfer inward through these thermal bridge areas, leading to uneven indoor temperature distribution. This uneven temperature distribution not only affects indoor comfort but may also cause energy waste. For example, in cold winter, heat quickly escapes through the thermal bridge, making the indoor areas near these connection points colder, affecting the comfort of the occupants. In summer, the indoor temperature rises due to external heat penetration, increasing the load on the air conditioning system. This temperature difference not only affects human comfort but also increases the energy consumption for indoor heating or cooling.

2.2 Convection

In prefabricated buildings, the convection heat transfer process is one of the important factors influencing the indoor thermal environment. Due to the presence of multiple connecting components in the prefabricated building structure, the temperature differences formed at these connection points by the thermal bridge effect cause local variations in indoor airflow. When certain areas indoors become colder due to the thermal bridge effect, the temperature difference drives air movement, causing convection between the cold and warm areas. This natural convection process not only accelerates heat transfer but may also lead to uneven airflow indoors, further affecting the thermal environment. For instance, the air near the thermal bridge is colder, and its density is higher, causing the cold air to sink, while the air in the warm areas rises. This convection movement may cause uneven temperature distribution in different indoor areas, making some areas too cold while others are warmer, thus affecting comfort.

The airflow indoors and the forced effect of equipment also influence the flow pattern of air within the building. For example, air conditioning or heating systems may create local air circulation in some areas, intensifying the heat exchange in areas associated with thermal bridges and increasing energy consumption in those areas. Furthermore, during the airflow process, the heat conduction effect between air molecules and the molecules of the wall surface also plays a significant role in convection heat transfer. The convective heat transfer amount on the building surface can be quantified further using Newton's formula for calculating the convective heat transfer, thus more precisely assessing the impact of the thermal bridge effect on the indoor thermal environment. Assuming the convective heat transfer intensity is represented by w, the convective heat transfer coefficient by β, the fluid temperature by s, and the solid surface temperature by ϕ, the convective heat transfer amount on the building surface can be expressed as:

$$w_z = \beta_z\left(s - \varphi\right) \tag{2}$$

The convection heat transfer in prefabricated buildings primarily affects the indoor thermal environment in terms of airflow distribution and temperature uniformity. Due to the local temperature differences caused by the thermal bridge effect, the characteristics of air movement are altered. The thermal bridge effect often causes areas near seams such as walls and window frames to be cooler, while areas far from the thermal bridge are warmer. This temperature difference not only causes changes in air density but also leads to natural convection. In cold weather conditions, cold air, being at a lower temperature, sinks to form cold air accumulation zones, while hot air rises, causing warm air to be unable to effectively cover the entire indoor space. As the airflow continues, certain areas inside the building may become too cold or too hot, creating significant temperature differences that affect occupant comfort. For example, areas near the thermal bridge may feel too cold, while areas far from the heat source may become too hot, resulting in an uneven indoor thermal environment.

In addition, convection in prefabricated buildings is also closely related to the use of air conditioning, heating, and other equipment. To compensate for the temperature difference caused by the thermal bridge effect, air conditioning or heating equipment may increase power to attempt to adjust the indoor temperature, but such adjustments are often local. Forced convection airflow can create different temperature fields in different regions, which may lead to energy waste and an increase in system load. Especially when the air conditioning or heating systems are operating, airflow can cause uneven heat distribution, making certain areas too hot or too cold, leading to the system continuously operating without effectively achieving energy savings. Prolonged uneven temperature distribution not only affects occupant comfort but also increases building energy consumption.

2.3 Radiation

Radiation heat transfer is the process in which prefabricated building unit modules emit electromagnetic waves, which are absorbed by other prefabricated building unit modules and converted into heat energy, influenced by the surface temperature and properties of the prefabricated building unit modules. The thermal bridge effect in prefabricated buildings causes temperature differences in certain areas, which in turn affects the radiation characteristics of these areas. The thermal bridge effect is commonly found in connection points such as walls, window frames, and floors, where these areas, due to faster heat conduction, typically have lower surface temperatures than other areas. In this case, high-temperature areas of the prefabricated building unit modules will radiate heat to low-temperature areas, creating radiation heat exchange. According to the Stefan-Boltzmann equation, the radiation heat transfer is proportional to the fourth power of the absolute temperature of the surface of the prefabricated building unit modules, so the greater the temperature difference, the greater the radiation heat transfer. This radiation heat transfer process will further exacerbate the uneven temperature distribution caused by the thermal bridge effect, affecting the indoor thermal environment. Assuming that the heat flux is represented by W, the Stefan-Boltzmann constant by δ, the area of radiation surface 1 by X_1, the shape factor from radiation surface 1 to radiation surface 2 by D_{12}, the absolute temperature of radiation surface 1 by S_1, and the absolute temperature of radiation surface 2 by S_2, the specific calculation formula is:

$$W = \gamma \delta X_1 D_{12} \left(S_1^4 - S_2^4 \right) \tag{3}$$

The radiation heat transfer in prefabricated buildings primarily affects the indoor thermal environment in terms of uneven temperature distribution and changes in indoor comfort. Due to the thermal bridge effect, certain areas have lower surface temperatures, especially at connection points like walls and window frames. Radiation heat transfer will occur between the high-temperature and low-temperature areas. High-temperature surfaces (such as areas near heat sources) will radiate heat to the cooler areas, and these cooler areas will absorb the radiant energy, thereby increasing their surface temperature. Since the transfer efficiency of radiation heat is proportional to the fourth power of the surface temperature, the greater the temperature difference, the more significant the radiation heat transfer effect. This local temperature difference not only intensifies the heat exchange caused by the thermal bridge effect but also leads to uneven temperature distribution inside the building. Some areas may become overheated due to radiation heat transfer, while other areas remain cold, affecting occupant comfort and the overall thermal environment of the space.

3. HEAT CONDUCTION DIFFERENTIAL EQUATION AND TEMPERATURE FIELD BOUNDARY CONDITIONS IN PREFABRICATED BUILDINGS

3.1 Heat conduction differential equation

In prefabricated buildings, the thermal bridge effect typically occurs at connection points such as the junctions between walls and window frames, and walls and floors, where the thermal conductivity is relatively high, leading to large temperature variations. According to Fourier's law, the transfer of heat is proportional to the temperature gradient, and heat always flows towards the direction of lower temperature. The temperature in the thermal bridge region is lower, so heat will flow from the warmer areas to the colder thermal bridge regions, causing heat to concentrate in these areas and form a large temperature gradient. The rate of heat flow can be calculated using Fourier's law, which is crucial for assessing the impact of the thermal bridge effect on the indoor thermal environment. Assuming the heat conduction area is represented by X, the thermal conductivity coefficient by η, and the temperature gradient by $GRADT$, the expression is:

$$\Theta = -X / GRADT \tag{4}$$

For unit area, assuming the heat flux density is represented by W, the above equation can be simplified as:

$$W = -\eta GRADT \tag{5}$$

In the complex multidimensional heat conduction problem of prefabricated buildings, although Fourier's law helps analyze one-dimensional steady-state heat conduction problems, it cannot directly address the multidimensional and unsteady heat conduction issues caused by the thermal bridge effect because it does not reveal the dynamic relationship between the temperature at each point and the temperature at neighboring points. Therefore, to deeply understand the impact of the thermal bridge effect on the indoor thermal environment, it is necessary to apply the heat conduction differential equation. By constructing the heat conduction differential equation, we can consider the inherent relationship between spatial coordinates and time, which allows us to describe and calculate the temperature distribution and heat flow in different parts of the prefabricated building, especially in the thermal bridge regions.

The construction of the heat conduction differential equation is based on the continuous transfer of heat in space. In prefabricated buildings, thermal bridge regions often have strong thermal conductivity, leading to large temperature gradients. This requires us to consider not only the thermal conductivity of the prefabricated building unit modules but also the local temperature differences caused by the thermal bridge effect when constructing the differential equation. In this case, the heat conduction differential equation can describe not only steady-state heat conduction but also reveal time variations in unsteady-state heat conduction. For example, the temperature inside the building changes over time, or how heat is transferred between different parts of the building under fluctuating external temperatures, especially in regions near thermal bridges. According to heat conduction theory, assuming the instantaneous temperature of the prefabricated building unit module is represented by S, the time during the heat conduction process by s, the thermal conductivity coefficients along the three principal axes of the material by η_a, η_b, η_c, the material density by ϑ, the specific heat capacity of the material by Z, and the intensity of the internal heat source by w_n, the differential equation for heat conduction in an orthotropic solid can be constructed as:

$$\frac{\partial}{\partial a}\left(\eta_a \frac{\partial S}{\partial a}\right)+\frac{\partial}{\partial b}\left(\eta_b \frac{\partial S}{\partial b}\right)+\frac{\partial}{\partial c}\left(\eta_c \frac{\partial S}{\partial c}\right)+w_n=\vartheta z \frac{\partial S}{\partial s} \tag{6}$$

Assuming there are no heat sources in the prefabricated building unit module and the material is isotropic, the above equation can be simplified to:

$$\frac{\partial S}{\partial s}=\frac{\eta}{oz}\left(\frac{\partial^2 S}{\partial a^2}+\frac{\partial^2 S}{\partial b^2}+\frac{\partial^2 S}{\partial c^2}\right) \tag{7}$$

3.2 Uniqueness condition in heat conduction process

In the study of the thermal bridge effect in prefabricated buildings, the uniqueness condition of the heat conduction process is crucial for accurately calculating heat transfer and temperature distribution. The uniqueness condition generally contains four components.

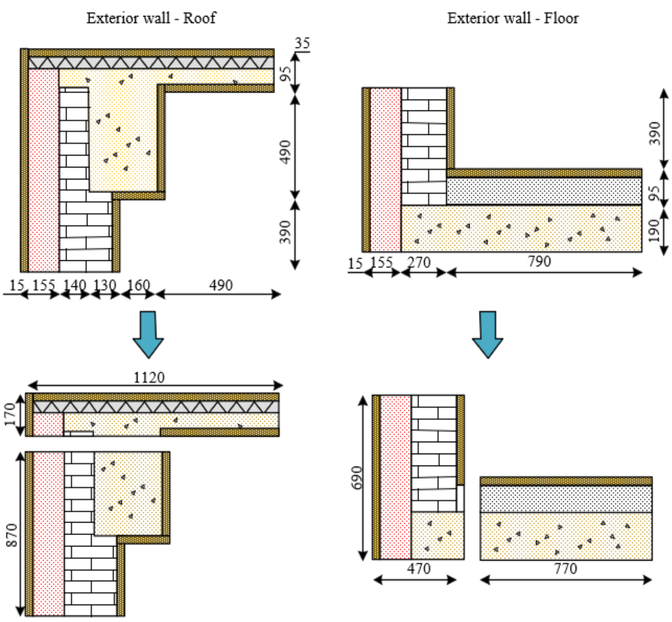

Figure 1. Thermal bridge calculation area division

(1) Geometric conditions. The thermal bridge effect typically occurs at connection points such as the junctions between walls and window frames, and walls and floors. By defining the geometric shapes and dimensions of these areas, we can better understand the process of heat transfer between different parts. For example, the thickness of the wall, the size of the window frame, and the structure of the floor all affect the temperature gradient and heat flow in the thermal bridge region. Figure 1 provides a specific example of the division of thermal bridge calculation areas. When constructing the heat conduction differential equation, these geometric factors must be considered because they directly determine the distribution of heat flow paths and the efficiency of heat conduction. The setting of geometric conditions ensures that we can correctly describe the flow of heat between different structural components in the prefabricated building.

(2) Physical conditions. This involves the physical properties of the prefabricated building unit modules that participate in the heat conduction process. In prefabricated buildings, there are significant differences in the thermal conductivity of different materials, especially in the thermal bridge areas, where the thermal conductivity coefficient of the material is crucial for heat transfer. For example, the material differences between the wall and the window frame may cause rapid temperature changes in localized areas due to the differences in thermal conductivity coefficients. Additionally, the thermal conductivity of the material may change with temperature variations, especially under extreme temperature conditions. At this point, physical conditions not only include the thermal conductivity coefficient of the material but may also involve the presence of internal heat sources, such as heat generated by equipment or cables, which can affect the distribution of heat and the heat conduction process. By determining these physical properties, we can further accurately describe the transfer of heat.

(3) Time conditions. For the thermal bridge effect in prefabricated buildings, especially when there are significant changes in external temperatures, the indoor temperature changes will also be influenced by time factors. For example, the temperature fluctuations between day and night, or seasonal changes, may lead to changes in the temperature difference between the interior and exterior of the building, which in turn affects the heat flow and heat transfer process. In these cases, appropriate initial conditions need to be set to describe the temperature distribution inside the building at a specific time, ensuring that the solution of the heat conduction differential equation can reflect the temperature changes over time, particularly in areas near the thermal bridge.

(4) Boundary conditions. In prefabricated buildings, boundary conditions usually involve the interaction between the building surface and the surrounding environment. The boundary conditions for the thermal bridge region can be divided into three types: The first type of boundary condition is the known temperature value on the boundary surface, which is usually set by measuring or assuming the temperature field. This is crucial for ensuring the accuracy of the heat transfer direction and rate. The second type of boundary condition is the known heat flux density on the boundary surface, which means that we can calculate the temperature gradient and subsequently deduce the heat flow during the heat conduction process by measuring the heat flux density based on Fourier's law. The third type of boundary condition involves the heat exchange coefficient between the prefabricated building unit module surface and the surrounding fluid, as well as the fluid temperature. This condition is typically used to describe the heat exchange between the building's exterior surface and the surrounding air, especially in winter or summer when the external environmental temperature influences the heat exchange between the inside and outside of the building. In the analysis of the thermal bridge effect, precisely setting these boundary conditions is crucial for obtaining accurate heat conduction solutions.

3.3 Heat transfer process of enclosure structures

Prefabricated buildings are typically composed of prefabricated components, and the connection points of these components are prone to form thermal bridge areas, which have higher thermal conductivity, causing heat to quickly dissipate from or enter the interior of the building. The heat transfer process of the enclosure structure generally includes three stages: surface heat absorption, heat conduction within the structure itself, and surface heat dissipation. In the context of the thermal bridge effect, heat flows through the enclosure structure from the warm interior to the cold exterior, or vice versa. This process is significantly influenced by the structural connection points. The heat transfer rate in the thermal bridge regions is higher because these areas have a higher thermal conductivity than the surrounding building materials, causing heat to concentrate in these regions, thereby exacerbating the uneven temperature inside the building and affecting overall thermal comfort.

In the enclosure structure of prefabricated buildings, the surface heat absorption process is particularly critical. The exterior surface of the building absorbs radiant heat from the external environment, especially in summer when the external temperature is high, causing heat to flow from the outside to the interior. In the thermal bridge area, this process may be more intense because the materials at the thermal bridge have stronger thermal conductivity, making it easier for heat to enter the interior through these parts. At the same time, the interior surface also absorbs heat transferred from the indoor air. Under the influence of the thermal bridge effect, the flow of heat tends to concentrate at these connection points, causing the temperature in these areas to rise and thereby exacerbating the uneven temperature distribution inside the building, affecting the thermal comfort. Table 1 shows the equivalent heat transfer coefficients of typical thermal bridges.

The heat transfer process of the enclosure structure in prefabricated buildings mainly impacts the indoor thermal environment through the flow of heat and the distribution of indoor temperature. Since the enclosure structure continuously experiences heat conduction under different seasonal and external environmental conditions, heat is transferred into and out of the building through these structures. Especially in the thermal bridge areas, the heat transfer rate is accelerated due to the higher thermal conductivity at the connection points, which causes significant temperature changes in localized regions, creating noticeable temperature differences. For example, in winter, heat flows out of the building through the thermal bridge, causing these areas to be colder, which can even lead to condensation. In contrast, in summer, the external high temperature enters the interior through the thermal bridge, raising the temperature in these areas and affecting the overall stability and comfort of the indoor temperature. Therefore, the thermal transfer characteristics of the enclosure structure directly impact the indoor thermal environment. Particularly in areas with significant thermal bridge effects, this may result in uneven temperatures, decreased comfort, and higher energy consumption.

In prefabricated buildings, the thermal conductivity process of the enclosure structure often involves issues similar to heat conduction in an infinitely large flat wall, especially in areas with significant thermal bridge effects. According to heat transfer theory, the setting of boundary conditions is crucial for solving the heat transfer problem.

Considering the first type of boundary condition, which is the known temperature on both sides. For the walls in prefabricated buildings, the wall surfaces are usually in contact with both the external environment and the interior space, so the temperatures on both sides are influenced by the external temperature and the internal temperature. In the thermal bridge areas, the connection between the wall and the window frame or other building components may cause differences in thermal conductivity due to the material and geometric characteristics. In such cases, heat flows from the higher temperature region to the lower temperature region, forming heat flux density. Using the concept of thermal resistance, we can calculate the heat transfer rate, and by optimizing the thermal conductivity characteristics of the thermal bridge region for different materials and joints, effectively reduce heat loss and improve the energy efficiency of the building. The boundary condition expression is:

$$\begin{cases} s\big|_{a=0} = s_{q_1}, \ s\big|_{a=\pi} = s_{q_2} \\ \dfrac{d^2 s}{da^2} = 0 \end{cases} \tag{8}$$

The solution is as follows:

$$s = s_{q_1} - \frac{s_{q_1} - s_{q_2}}{\sigma} a \tag{9}$$

Let σ/η be the thermal resistance, and the heat flux density expression is:

$$w = -\eta \frac{ds}{da} = \eta \frac{s_{q_1} - s_{q_2}}{\sigma} = \frac{s_{q_1} - s_{q_2}}{\sigma / \eta} = \frac{\Delta s}{E_s} \tag{10}$$

Table 1. Equivalent heat transfer coefficients of typical thermal bridges

Thermal Bridge Structure	Corner Column	T-Shaped Column	Exterior Wall - Roof	Exterior Wall - Floor	Exterior Wall - Slab
Area Weighted Heat Transfer Coefficient $J_1/W.(m^2.K)^{-1}$	0.235	0.215	Roof 0.132 Exterior Wall 0.224	0.221	0.217
2D Equivalent Heat Transfer Coefficient $J_2/W.(m^2.K)^{-1}$	0.278	0.217	Roof 0.211 Exterior Wall 0.259	0.265	0.228
Relative Error $(J_2-J_1)/K_2$	14%	-3%	Roof 28% Exterior Wall 22%	22%	12%

The heat conduction quantity calculation formula is:

$$w=\frac{s_{q_1}-s_{q_{(v+1)}}}{\sum_{u=1}^{v}E_{s,u}}=\frac{s_{q_1}-s_{q_{(v+1)}}}{\frac{\sigma_1}{\eta_1}+\frac{\sigma_1}{\eta_1}+\cdots+\frac{\sigma_v}{\eta_v}} \tag{11}$$

The second type of boundary condition considers the known heat flux density at a point on the surface of a unit module of the prefabricated building. This condition is particularly applicable to the heat exchange between the wall surface and air in prefabricated buildings. The variation in surface heat flux density is mainly influenced by external climate conditions and the external environment of the wall. In regions where the thermal bridge effect is significant, the heat flux density becomes uneven due to local differences in thermal conductivity characteristics. For example, the thermal conductivity in the thermal bridge area is stronger, leading to a higher heat flux density in these areas compared to others, which in turn affects the overall heat transfer process. Therefore, setting reasonable heat flux density boundary conditions helps more accurately calculate the thermal transfer characteristics of the wall, especially at seams and connections with significant thermal bridge effects, reducing indoor temperature fluctuations caused by uneven heat flux density, and thus improving residential comfort. Given the heat flux density at any point on the surface of a unit module of the prefabricated building, assuming the surface of the prefabricated building is represented by t and the normal is represented by v, the heat flux density expression is:

$$\left(w_v\right)_t=d\left(s\right) \tag{12}$$

The heat flux on the boundary of the object is a known function of time, and the above equation can be rewritten as:

$$-\eta\left(\frac{\sigma s}{\sigma v}\right)_t=\left(w_v\right)_t=d\left(s\right) \tag{13}$$

At an adiabatic boundary, the heat flux density is assumed to be zero, so:

$$\left(\frac{\sigma s}{\sigma v}\right)_t=0 \tag{14}$$

The third type of boundary condition is used to describe the heat exchange between the surface of the object and the surrounding fluid. In prefabricated buildings, the heat exchange between the surface of the enclosure structure and the external environment significantly affects the building's thermal environment, especially in the thermal bridge regions at the junctions of window frames and exterior walls. In these regions, the temperature variation of the external air directly influences heat transfer. By setting the third type of boundary condition, the heat flux and temperature distribution in these areas can be better described. For example, when the external temperature is lower, heat will quickly flow from the thermal bridge region to the outside, while when the external temperature is higher, heat will flow from the outside into the interior. By reasonably setting these boundary conditions, the thermal transfer performance of the building's enclosure structure can be accurately calculated and optimized, reducing the negative impact of the thermal bridge effect on indoor temperature and enhancing the thermal stability of the building. Let the object being studied be an infinitely large flat wall with thickness σ, assuming the fluid temperatures on both sides of the flat wall are represented by s_{d1} and s_{d2}, and the surface heat transfer coefficients of the fluids on both sides are represented by g_1 and g_2, the heat flux density expression is:

$$w=\frac{s_{d_1}-s_{d_2}}{\frac{1}{g_1}+\frac{\sigma}{\eta}+\cdots+\frac{1}{g_2}} \tag{15}$$

4. EXPERIMENTAL RESULTS AND ANALYSIS

According to the experimental data in Table 2, the heat loss degree at thermal bridge locations in prefabricated buildings can be observed. As the thermal conductivity of the outer main wall increases, the heat loss of the thermal bridge also gradually increases. When the thermal conductivity is 0.15, 0.41, and 0.81 $(m.K)^{-1}$, the one-dimensional equivalent heat transfer coefficient increases from 0.87 to 2.15, while the corresponding three-dimensional total heat loss increases from 612.52 *W.h* to 1341.25 *W.h*. This indicates a close relationship between the thermal bridge effect and thermal conductivity, i.e., materials with stronger thermal conductivity lead to more heat loss. Furthermore, from the underestimated heat loss ratio, it can be seen that as the thermal conductivity increases, the ratio of underestimated heat loss gradually decreases, indicating that the three-dimensional heat loss evaluation method is more accurate, especially for high-conductivity materials. This result reveals that the heat loss in prefabricated buildings under the thermal bridge effect is significant, particularly when high-conductivity materials are used. A comprehensive analysis of the experimental results shows that the impact of the thermal bridge effect on the indoor thermal environment increases with the increase in the thermal conductivity of the exterior wall. The thermal bridge effect causes heat to transfer from the building's exterior to the interior, resulting in uneven indoor temperature distribution, which affects occupant comfort and energy consumption. The use of high-conductivity materials leads to more heat loss, so in the design of prefabricated buildings, high-conductivity materials should be avoided at thermal bridge locations, or effective insulation measures should be taken to reduce the negative impact of the thermal bridge effect.

According to the experimental data in Table 3, it can be seen that the heat transfer coefficient of the prefabricated building enclosure structure is significantly affected by the different exterior wall main thermal conductivities (0.15, 0.41, 0.81 $(m.K)^{-1}$). The heat transfer coefficients of EPS and XPS materials are relatively stable, varying from 0.102 to 0.061, while the heat transfer coefficient of STP material decreases significantly from 0.031 to 0.011. This indicates that STP material has a strong effect in reducing thermal conductivity. The heat transfer coefficients of the exterior wall, roof, and ground decrease as the thermal conductivity of the exterior main wall increases. For example, the heat transfer coefficient of the exterior wall decreases from 0.458 to 0.325, the roof from 0.623 to 0.226, and the ground from 0.735 to 0.485. These data suggest that in the case of a high-conductivity exterior main wall, the heat loss of other enclosure components decreases, but the overall heat transfer coefficient remains high, especially in the ground area. The experimental results show that although some high-performance insulation materials perform excellently in reducing the thermal bridge effect, the thermal conductivity of the exterior main wall still has a significant impact on the indoor thermal environment of prefabricated buildings. As the thermal conductivity of the exterior main wall increases, the heat transfer coefficient of the enclosure structure gradually decreases, indicating that the overall heat loss of the building is still relatively high, which negatively impacts the uniformity of indoor temperature and energy efficiency. Therefore, in the design of prefabricated buildings, low thermal conductivity materials should be prioritized, and comprehensive measures should be taken, such as adding insulation layers or optimizing structural node designs, to effectively reduce the thermal bridge effect and improve the thermal performance and energy efficiency of the building.

Table 2. Heat loss degree at thermal bridge locations in prefabricated buildings

Exterior Wall Main Thermal Conductivity/$(m.K)^{-1}$	0.15	0.41	0.81
Affected Area/m²	0.44	0.44	0.44
Thermal Bridge Area/m²	0.04	0.04	0.04
One-dimensional Equivalent Heat Transfer Coefficient/W/(m².K)$^{-1}$	0.87	1.48	2.15
One-dimensional Equivalent Total Heat Loss/W.h	554.26	987.52	1235.26
Three-dimensional Total Heat Loss/W.h	612.52	1124.23	1341.25
Underestimated Heat Loss Ratio	6.59%	1.89%	0.67%

Table 3. Heat transfer coefficients of prefabricated building enclosure structures under different exterior wall main thermal conductivities

Exterior Wall Main Thermal Conductivity /$(m.K)^{-1}$	0.15	0.41	0.81
EPS	0.102	0.081	0.061
XPS	0.102	0.081	0.061
STP	0.031	0.021	0.011
Exterior Wall	0.458	0.389	0.325
Roof	0.623	0.432	0.226
Ground	0.735	0.615	0.485

Table 4. Two-dimensional equivalent heat transfer coefficients of thermal bridges in prefabricated buildings under different exterior wall thermal conductivity coefficients

Exterior Wall Thermal Conductivity/$(m.K)^{-1}$	0.15	0.41	0.81
Exterior Wall - Floor	0.541	0.452	0.356
Exterior Wall - Ground	0.556	0.479	0.387
Exterior Wall - Roof	Roof 0.625	0.556	0.325
Exterior Wall	Exterior Wall 0.715	0.562	0.426
T-type Column	0.478	0.412	0.326
Corner Column	0.635	0.536	0.435

According to the experimental data in Table 4, it can be observed that under different exterior wall thermal conductivity coefficients (0.15, 0.41, 0.81 $(m.K)^{-1}$), the two-dimensional equivalent heat transfer coefficients of thermal bridges in prefabricated buildings show a certain regular variation. Specifically, as the thermal conductivity of the exterior wall increases, the two-dimensional equivalent heat transfer coefficients of each thermal bridge generally decrease. For example, the heat transfer coefficient of the exterior wall-floor decreases from 0.541 to 0.356, from 0.556 to 0.387 for the exterior wall-ground, from 0.625 to 0.325 for the exterior wall-roof, from 0.478 to 0.326 for the T-type column, and from 0.635 to 0.435 for the corner column. This phenomenon indicates that when the exterior wall has a higher thermal conductivity, the heat flux density of the thermal bridge locations decreases, resulting in a reduction in the two-dimensional equivalent heat transfer coefficient. From the experimental results, it can be concluded that although the exterior wall with high thermal conductivity can reduce the two-dimensional equivalent heat transfer coefficient of thermal bridges to a certain extent, the overall thermal bridge effect still has a significant impact on the indoor thermal environment. The use of high thermal conductivity materials not only increases the temperature difference between the inside and outside, affecting the uniformity and comfort of indoor temperatures, but also increases the overall heat loss of the building, leading to higher energy consumption. Therefore, in the design of prefabricated buildings, it is advisable to choose materials for the exterior walls with low thermal conductivity and combine them with optimized thermal bridge designs, such as adding insulation layers or using better thermal insulation node treatments, to effectively reduce the negative impact of thermal bridges on the indoor thermal environment.

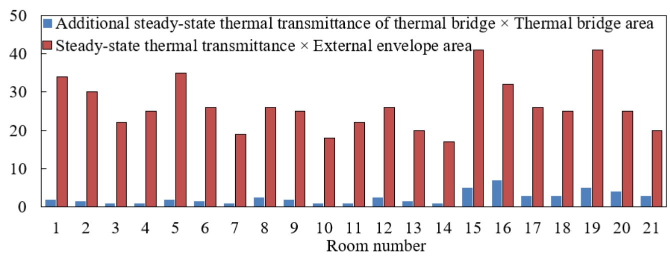

Figure 2. Product of additional steady-state heat transfer coefficient and area of thermal bridges in prefabricated buildings

According to the data in Figure 2, the product of the additional steady-state heat transfer coefficient of thermal bridges and the area of thermal bridges, as well as the product of the steady-state heat transfer coefficient and the exterior envelope area, show significant variation across different rooms. The data indicate that the values of the product of the additional steady-state heat transfer coefficient and the thermal bridge area range from 1 to 7. For example, the value for Room 1 is 2, while for Room 16, it is 7, indicating a large difference in the degree of the thermal bridge effect between different rooms. Similarly, the product of the steady-state heat transfer coefficient and the exterior envelope area varies from 17 to 41, with Room 13 having a value of 20, while Room 15 has a value of 41. Comparing these values reveals that the thermal bridge effect varies significantly between rooms, and its impact is more pronounced in rooms with high additional steady-state heat transfer coefficients. It is evident that the thermal bridge effect significantly affects the uniformity of the indoor thermal environment and the overall energy efficiency of the building. Rooms with higher additional steady-state heat transfer coefficients, such as Rooms 16 and 15, show greater heat loss, leading to larger temperature fluctuations in these rooms and increased heating and cooling energy consumption. Moreover, the data of the product of the steady-state heat transfer coefficient and the exterior envelope area indicate that the difference in the thermal performance of the exterior envelope structure between rooms also has a significant impact on the thermal bridge effect. Therefore, when designing and constructing prefabricated buildings, special attention should be paid to the handling of thermal bridge locations, using materials with low thermal conductivity and optimizing node designs to reduce the negative impact of thermal bridges on the indoor thermal environment.

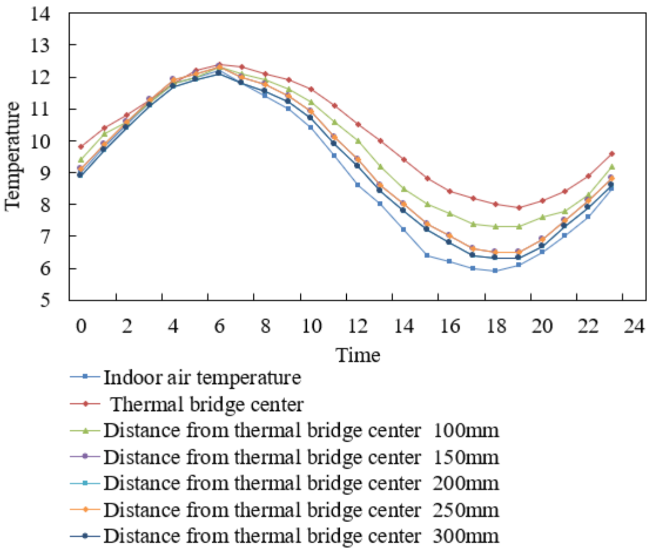

Figure 3. Temperature variation curve of indoor measurement points in prefabricated buildings

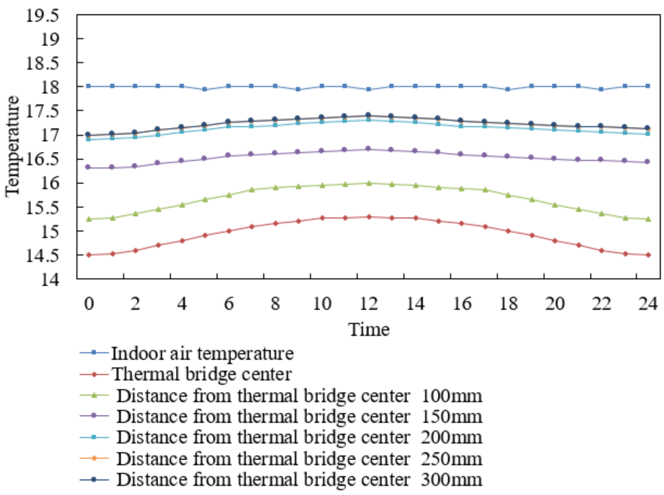

Figure 4. Temperature variation curve of outdoor measurement points in prefabricated buildings

Based on the experimental data in Figures 3 and 4, the temperature variation trends at indoor and outdoor measurement points show that the thermal bridge effect significantly fluctuates at different times, affecting the indoor thermal environment. The indoor air temperature gradually decreases from 9°C to 6.5°C over the time period from 0 hours to 22 hours. Meanwhile, the temperature at the thermal bridge center increases from 9.8°C to 12.4°C, indicating that the temperature in the thermal bridge area is significantly higher than that of the surrounding environment. At measurement points located at different distances from the thermal bridge center, the temperature gradually decreases but still maintains an upward trend, especially in areas close to the thermal bridge, where the temperature is notably higher compared to areas farther away. These data suggest that the temperature rise in the thermal bridge area affects the indoor temperature, and the heat transfer through the thermal bridge region leads to a local temperature increase. According to the experimental results, the thermal bridge effect causes a significant uneven distribution of indoor temperature, especially near the thermal bridge, where the indoor temperature is higher, while areas far from the thermal bridge have noticeably lower temperatures. This phenomenon indicates that thermal bridges not only increase heat loss but also affect the comfort of the indoor thermal environment. Over time, the thermal bridge effect becomes more pronounced indoors, and this effect may have different impacts in different rooms or locations. To reduce the negative impact of the thermal bridge effect on the thermal environment, more reasonable thermal bridge treatment measures, such as adding insulation layers and improving the structural design of thermal bridge locations, can be adopted in the design and construction of prefabricated buildings to reduce the interference of thermal bridges on the indoor thermal environment, improving energy efficiency and residential comfort.

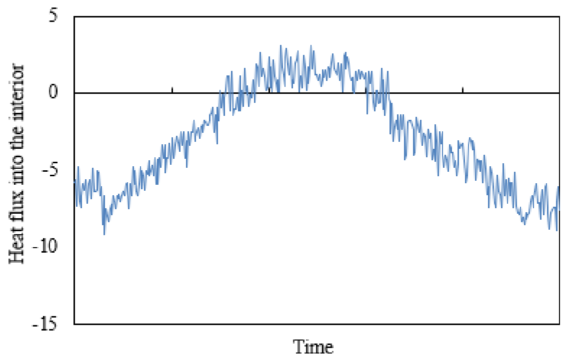

Figure 5. Heat flow transferred into the indoor thermal bridge of prefabricated buildings

From the heat flow data of the indoor thermal bridge transferred into the prefabricated building, shown in Figure 5, the heat flow intensity exhibits obvious fluctuating characteristics over time. The heat flow intensity fluctuates around 0, with positive values indicating that heat is transferred into the indoor space through the thermal bridge, and negative values indicating that heat flows out of the indoor space through the thermal bridge, with varying fluctuation amplitudes. These data characteristics directly reflect the dynamic changes in the direction and intensity of heat flow through the thermal bridge over time, demonstrating the complex influence of the thermal bridge on indoor heat exchange at different times. The thermal bridge effect leads to a decrease in the stability of the indoor thermal environment. When the heat flow intensity is positive, the thermal bridge serves as a conduit for heat entering the indoor space, potentially raising the indoor temperature during certain periods; when the heat flow intensity is negative, indoor heat is lost through the thermal bridge, intensifying heat loss. This alternating positive and negative heat flow fluctuation indicates that the thermal bridge damages the thermal insulation performance of the building envelope, causing the indoor temperature to fluctuate unexpectedly with changes in the external environment. This ultimately makes it difficult to maintain a stable indoor thermal environment, which affects both comfort and presents a challenge to the building's energy-saving objectives.

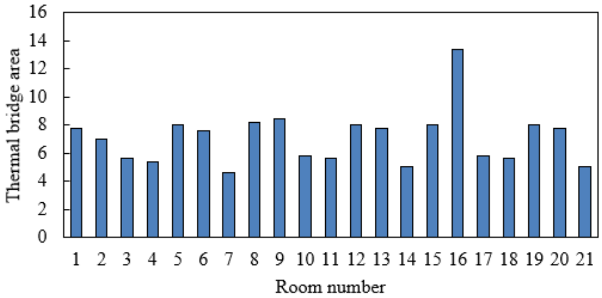

Figure 6. Area of thermal bridge affected region in each room of prefabricated building

Based on the data in Figure 6, the thermal bridge areas in each room show certain differences, ranging from 4.6 square meters to 13.4 square meters. For example, the thermal bridge area in Room 1 is 7.8 square meters, while Room 16 has a thermal bridge area of 13.4 square meters, and Room 7 has the smallest thermal bridge area of only 4.6 square meters. The difference in thermal bridge areas directly affects the strength of the thermal bridge effect in each room. In prefabricated buildings, thermal bridges are usually heat transfer channels between the building envelope and the indoor environment. An increase in the thermal bridge area makes it easier for heat to transfer through the thermal bridge, leading to greater heat loss and larger indoor temperature fluctuations. Rooms with larger thermal bridge areas, such as Room 16, experience more severe heat loss, which may result in lower and more uneven indoor temperatures in those areas. In contrast, rooms with smaller thermal bridge areas, such as Room 7, are less affected. By analyzing this data, the most likely conclusion regarding the thermal bridge effect on the indoor thermal environment in prefabricated buildings is as follows: rooms with larger thermal bridge areas have significantly higher heat loss, and the negative impact of the thermal bridge effect on the indoor thermal environment is more pronounced. These rooms may experience greater temperature fluctuations, which affect comfort, especially when external temperatures fluctuate significantly, as the thermal bridge effect may exacerbate temperature unevenness. To address this issue, insulation measures can be added during the design of prefabricated buildings, particularly in thermal bridge areas, to reduce the thermal bridge area, or structural components can be improved to reduce the thermal bridge effect. This will help improve the indoor temperature balance and living comfort, while reducing energy consumption.

According to the data in Figure 7, the average additional steady-state heat transfer coefficient of the thermal bridges in each room shows significant differences, ranging from 0.3 to 0.73. For example, the heat transfer coefficient in Room 1 is 0.36, while the heat transfer coefficient in Room 21 reaches 0.73. It can be observed that Rooms 15, 19, and 21 have higher heat transfer coefficients, with values of 0.7, 0.7, and 0.73 respectively, while Rooms 2, 3, and 4 have lower heat transfer coefficients, with values of only 0.3. These data suggest that rooms with higher heat transfer coefficients allow heat to be transferred through the thermal bridge more efficiently, leading to greater heat loss, and making it harder to maintain stable indoor temperatures. Rooms with lower heat transfer coefficients experience less heat loss, and their indoor temperatures are easier to stabilize. By analyzing this data, the most likely conclusion regarding the thermal bridge effect on the indoor thermal environment in prefabricated buildings is as follows: the higher the average additional steady-state heat transfer coefficient of the thermal bridge, the greater the heat loss in the room, which leads to more significant indoor temperature fluctuations and reduced comfort. Rooms with higher heat transfer coefficients will lose more heat in winter and absorb more heat in summer, causing instability in indoor temperatures. To reduce the impact of the thermal bridge effect on the indoor thermal environment, measures can be taken during the design and construction of prefabricated buildings to lower the heat transfer coefficient of the thermal bridges, such as using efficient insulation materials, optimizing building structure design, and adding insulation layers at thermal bridge locations. These measures can effectively reduce the thermal bridge effect, improve the stability and comfort of the indoor thermal environment, and enhance the building's energy efficiency.

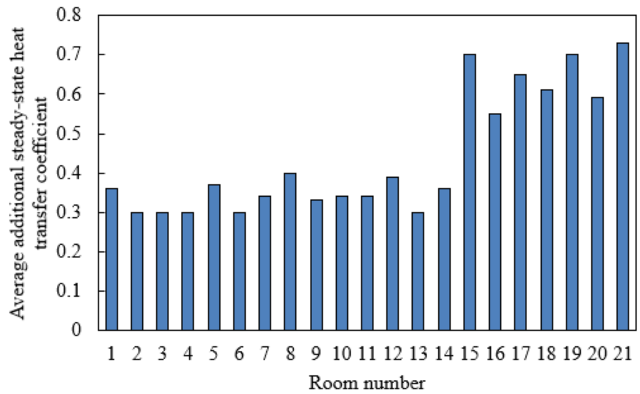

Figure 7. Average additional steady-state heat transfer coefficient of thermal bridges in rooms of prefabricated buildings

5. CONCLUSION

This paper conducted an in-depth study on the thermal bridge effect in prefabricated buildings and its impact on the indoor thermal environment. It first explored the formation mechanism of the thermal bridge effect and analyzed the contribution of different structural components to the thermal bridge effect. By establishing a heat conduction model and constructing the thermal differential equation and temperature field boundary conditions for the prefabricated building, this study used a combination of numerical simulation and experimental validation to analyze the influence of the thermal bridge effect under different temperature fields. The experimental data show that the area of the thermal bridge and the additional steady-state heat transfer coefficient have a significant impact on the indoor thermal environment. Rooms with higher heat transfer coefficients experience greater heat loss, leading to increased indoor temperature fluctuations, affecting residential comfort. By designing and optimizing the structure of the thermal bridge areas and using efficient insulation materials, the thermal bridge effect can be effectively reduced, improving the stability and comfort of the indoor thermal environment.

Based on the findings of this study, the following conclusions can be drawn: the thermal bridge effect significantly impacts the thermal environment of prefabricated buildings, especially in rooms with larger thermal bridge areas and higher heat transfer coefficients, where heat loss is more severe, and indoor temperature fluctuations are more pronounced, negatively affecting residential comfort and energy efficiency. This study provides important theoretical basis and practical guidance for thermal bridge treatment in prefabricated buildings, offering significant research value. However, there are certain limitations to this study, such as the experimental conditions that may affect the generalizability of the results and the need for further improvement in the accuracy of the numerical simulation model. Future research should focus on further optimizing thermal bridge treatment techniques, developing more efficient insulation materials, improving the precision of numerical simulations, and conducting validations in a wider range of building types and climate conditions to comprehensively improve the thermal environment performance and energy efficiency of prefabricated buildings.

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