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Improvement of Airtightness for Lightweight Prefabricated Building Envelope through Optimized Design of Panel Joints

Zhenghao Lin^{1,2}, Yehao Song^{1,2,*} and Dongchen Han^{1,2}

¹School of Architecture, Tsinghua University, Beijing, China ²Key Laboratory of Urban-Rural Eco Planning and Green Building, Ministry of Education, Beijing, China E-mail: zhenghao.lin@foxmail.com

Abstract. Airtightness of building envelope is a key factor affecting the indoor comfort, air quality, structural durability and energy efficiency, especially for the lightweight prefabricated building systems aiming to achieve the nearly zero energy goals. For panelised systems, the air mainly leaks through the openings and panel joints. However, most current studies concentrate on the airtightness of the former ones, such as windows and doors, studies on joint design are relatively rare. As a result, this study firstly proposes two joint prototypes, the straight joints and the special-shaped joints, with various design parameters. Secondly, the air infiltration volume for different joints are simulated and calculated by the CFD method. Besides, the volume was further compared to find out the optimized joint design. Finally, the airtightness requirements of Passivhaus are used to evaluate the performance of the optimized tongue and groove joint with the conventional straight ones. The results prove that the well-designed joints deliver better airtightness especially for the high-performance standard buildings.

Keywords: Air tightness; CFD; lightweight prefabricated buildings; panel joints; energy efficiency; nearly zero energy buildings

1. Introduction

Airtightness refers to the ability of building envelope to resist air infiltration. Not only can unorganized air infiltration gravely affects indoor comfort, air quality and building durability, but also causes huge extra energy consumption. Therefore, improving the overall airtightness of buildings has been the common ground for high-performance and low-energy consumption architectural research in recent years. For example, nearly zero energy building systems (NZEBs) like Germany's Passivhaus, Italy's Casaclima, and Switzerland's Minergie-P have all introduced unequivocal airtightness indicators [1].

In China, how to realize the nearly zero energy consumption of prefabricated buildings has evolved into one of the hot spots in architecture. However, because the prefabricated buildings, especially the lightweight ones, are usually assembled with composite sandwich panels and the like, whose joints tend to be the Achilles heel of the overall airtightness [2]. On the one hand, the "narrow and deep" joints in lightweight prefabricated buildings (LPBs) inflict difficulties in sealing on the construction site; on the other hand, the aging of the seal fillings will result in the exposure and infiltration. Thus, the airtightness of LPBs cannot be resolved solely by the construction accuracy and material performance. Instead, from the perspective of tectonics, this paper discusses how to improve the foundational airtightness through the optimized design of the panel joints.

Currently, the research into airtightness primarily focuses on three facets. First, as for the air leakage of door and window gaps, relevant research has established a predictive model based on experiments and experience, such as the "gap method" [3]. The α and b in the formula $Q = \alpha (\Delta P)^b$ are characteristic variables of infiltrated wind, which are subject to the influences of such factors as gap widths, geometric

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Corresponding author. Tel.: +86 010 62785691. E-mail address: ieohsong@tsinghua.edu.cn (Y.Song).

shapes, and actuating pressure differences. Yet, as the size, shape, connection mode and service state of the panel joints of LPBs still quite differ from those of doors and windows, their applicability remains to be tested. Second, some research focuses on the influencing mechanism of air infiltration on energy consumption, which sees the indoor air exchange frequency as the airtightness variable to simulate the change of indoor energy consumption under specific climate conditions, thus determining the airtight grade based on the energy conservation laws and regulations [4]. Nevertheless, such research rarely compares influences of different structure designs of joints on the airtight grade. Ultimately, the current research into building airtightness with nearly zero energy buildings is chiefly based on field measurement of "blower-door-test" upon completion [5]. Yet, its experimental difficulties and costs are higher, making it hard to systematically compare and analyse varying joints and structures

Therefore, this paper leverages Airpak 3.0, a Computational Fluid Dynamics (CFD) simulation software, to compare the influences of different structural design parameters of the panel joints of LPBs on air infiltration, taking account of the construction efficiency.

2. Methodologies

2.1. About Airpak 3.0

Airpak is a CFD software designed for building environment, which takes Fluent as the solution core and adopts a finite volume method based on unstructured grids. It can simulate the physical phenomena such as air flow, heat transfer and pollution in the research object. In this study, Airpak 3.0 is adopted to simulate the panel joints of LPBs.

2.2. Modelling and parameter setting

A $2m\times2m\times0.2m$ vertical wall is set up as CFD model in this study, which is formed by two horizontal panels, with a vertical joint at the centre axis of the wall. As this study focuses on the air flow phenomenon at the joint, the wall panel model is placed in a $2m\times2m\times8m$ tubular flow field (Figure 1). The wall divides the tubular flow field into two small ones, representing the outdoor and indoor environment. As per the "blower-door-test", a stable pressure difference ΔP perpendicular to the wall is applied to both ends of the flow field (usually 50pa), forcing outdoor air to infiltrate into indoor spaces via joints. By simulating the median cross section of the flow field as the representative plane (Figure 2), the average wind speed of the outlet side of the joint chamber is obtained, and the total volume of air penetrating through the joint per second is calculated and used as the evaluation indicator of joint airtightness. The calculation method is described in formula 1.

$$Q = F \cdot v_i = w \cdot l \cdot v_i \tag{1}$$

In this formula, Q represents the air infiltration volume (m³/s), F stands for the area (m²) of the indoor air outlet of the joint chamber, v_j refers to the average wind speed (m/s) of air outlet, w signifies the width (m) of the air outlet, and l represents the unit length (m) of the air outlet (1m by default).



Figure 1. CFD wall panel model (exemplified by the straight joint).



Figure 2. A cloud atlas of the wind speed of the Airpak's wall panel cross section.

2.3. Prototype classifications of joints and simulation arrangements

The panel joint prototypes of LPBs can be divided into straight joints and special-shaped joints, of which the latter ones are mainly categorized into staggered joints and tongue and groove (T&G) joints (Figure 3). For the convenience of simulation and discussion, this paper simplifies the prototypes of these joints

and simulates the influences of different structural design parameters on their airtight performance by control variables.



Figure 3. Three types of joint prototypes: a. straight joint, b. staggered joint, c. tongue and groove joint.

3. Results and discussions

3.1. Simulation of the straight joints

The straight joints are simple in structure, low in costs, hard to be damaged and good for the universality of construction. However, they easily cause air leakage. Therefore, this paper discusses the effects of two basic design parameters of the depth and width of joints on airtightness (Figure 4).



Figure 4. Geometric parameters of straight joints: a. depth of joint and b. width of joint.

3.1.1. Depth of joint. For straight joint, the depth equals the thickness of the envelope panel. A 2mmwidth straight joint is selected to simulate and compare the effects of various joint depths ranging from 50mm to 400mm on airtightness. As shown in Figure 5, with the increase of panel thickness, the volume of infiltrated air through the joint continuously drops. When the panel is thicker than 100mm, the air tightness at the joint is greatly improved; when the panel is thicker than 200mm, the downward curve of air infiltration gets gentle, indicating a limited increase in airtightness. Therefore, for straight joints, the panel thickness should be around 200 mm, too thin an insulation (< 200 mm) does not help achieve the insulation performance of NZEB. On the other hand, too thick plates (\geq 200 mm) will undermine the overall construction efficiency of LPBs.

3.1.2. Width of joint. The width of joints in this simulation does not refer to the "designed width", it instead should be interpreted as the "tightness" between panels, characterizing the fineness of the assembly construction or the performance of the sealing material. 17 sets of data are included in this group of simulations, covering the width from 0.5 mm to 10 mm. As shown in Figure 6, with the increase of the width, the air infiltration will also increase. The Origin 9.0 statistical software is used to regress the data. When the width is within 5mm, it is exponentially related to the air infiltration (R^2 =0.998) (Figure 7); when it is over 5mm, there is a significant linear relationship (R^2 =0.999) (Figure 8), suggesting different mechanisms of air infiltration. However, both manifest strong positive correlation, namely the narrower joint, the better. That not only requires better manufacturing and assembly quality, but also calls for the architects' awareness of gap control at the design stage.

As such, this paper chooses 2mm as the default joint width for subsequent simulation: first, the 2mm can characterize the air infiltration mechanism within the width range of 0-5 mm; second, adopting the 2mm joint width helps more to improve the quality of Airpak grid division.



Figure 5. Relation between air leakage and depth of joint.



Figure 6. Relation between air leakage and width of joint.



Figure 7. Fitting curve of airtightness (width within 5mm).



Figure 8. Fitting curve of airtightness (width over 5mm).

3.2. Simulation of special-shaped joints

Compared with straight joints, the special-shaped joints can provide a longer air flow path, and their "mutually embedded" panel-end can improve the assembly efficiency of building envelope. Therefore, this section of the study focuses on the improvement of airtightness while considering the construction efficiency, so as to find the optimized joint by comparing different geometric parameters (Figure 9).



Figure 9. Geometric structural parameters of T&G joints: a. number b. length c. width d. position.

3.2.1. Tongue and groove number. The T&G number represents the complexity of the joint structure. The simulation sets five groups of joints for comparison with different T&G numbers (Figure 10).



Figure 10. Five groups of joint structures with different T&G numbers for simulation.

As shown in Figure 12, the air infiltration volume of the special-shaped joints is lower than that of the straight joints, but the airtightness improvement of the staggered joint is insignificant, indicating that T&G joints are better. On the other hand, with the increase of T&G number, the joint airtightness is also improved. Nonetheless, complicated panel-end structures are bound to cause higher production costs, processing difficulties and transportation restrictions, and hence more mature LPBs in the market often adopt staggered joints or single T&G joints. After all-round deliberations, this paper chooses the prototype of single T&G joint for further simulation.

3.2.2. Tongue and groove length. The T&G length is one of the core parameters of the T&G joints. This simulation set nine T&G lengths (0~200mm) for comparison. As shown in Figure 13, as the length increases, the air infiltrating through the joint gradually declines with a linear trend, indicating that the longer the T&G is, the better the airtightness is.

From the perspective of construction, over-length T&G will not only exacerbate the difficulty of panel prefabrication, but also inflict damages on transportation and installation; additionally, the joint with large depth is hard to seal on site, thus inducing higher risks of air leakage. According to the author's study, most manufacturers suggest that the T&G length should not exceed 1/2 of the panel thickness. Thus, this paper chooses a 100 mm T&G length as the basic condition for subsequent simulation.

3.2.3. Tongue and groove width. This paper compares the airtight performance of joints with different T&G widths. Eight groups of data (40~180 mm) are given in the simulation. As shown in Figure 14, as the width grows, the air infiltration increases, with its amplitude being very small and basically negligible. It suggests that the T&G width is not a key factor affecting the airtightness of joints. Meanwhile, like the T&G length, the width should not be less than 1/2 of the panel thickness for the sake of structural rationality. Therefore, a 100mm T&G width is used in the following study.

3.2.4. Tongue and groove position. The relative position of the T&G towards the panel depth is another design parameter for single T&G joint. This simulation sets a total of 5 types of T&G positions for comparison (Figure 11). As can be seen from Figure 15, when the T&G position is closer to air outlet (low pressure area), the smaller the air infiltration through the joint, indicating a quite significant linear relationship. It shows that the positional relationship of the T&G structure is one of the key factors affecting the airtightness.



Figure 11. Five tongue and groove positions.



3.3. A comparison of the optimized tongue and groove joint and the straight joint

Based on the above simulation, this paper extracts the "innermost" single T&G joint obtained from Section 3.2.4 as the "optimized joint" and takes the straight joint as the "conventional joint", so as to further compare their airtight performance under different ΔP ranging from 5pa to 50pa.

As shown in Figure 16, the larger ΔP is, the greater air infiltration volume of two types of joints is; besides, the airtightness of the optimized T&G joint is continuously significantly better than that of the straight one. However, if the difference between two joints is compared, the smaller ΔP , the more obvious the airtight improvement of the optimized one. For example, under the ΔP of 5pa, the air infiltration of the optimized T&G joint can be reduced by 57.3 % compared with that of the straight one; yet under the ΔP of 50pa, the figure is only 32.6%. As ΔP mostly ranges from 5~20pa in actual operating conditions, thus the optimized T&G joint is more practical. Besides, to verify the feasibility of applying the "gap method" to LPBs joints, the author has regressed and fitted the airtight data of the two in the form of power exponent equation $Q = \alpha (\Delta P)^b$, discovering the R² indicator could reach 0.998 (Figure 17) and 0.997 (Figure 18) respectively. That is, the fitting is very ideal, which shows that the "gap method" was applicable to the estimation of the air infiltration of the panel joints of LPBs.



Figure 16. Relation between airtightness and ΔP .



Figure 17. Fitting curve of airtightness under different ΔP (the straight joint).



Figure 18. Fitting curve of airtightness under different ΔP (the optimized T&G joint).

Since the goal of the optimized design of joints is to realize nearly zero energy consumption of LPBs, the airtight requirements of Passivhaus (n50 ≤ 0.6 /h) are introduced to gauge the performance of the above two types of joints. This paper pre-sets a building with a net indoor size of 3m×3m×3m, with its each facade composed of three prefab panel, with a total of 12 vertical joints, and the total length is 36m (Figure 19). According to Passivhaus, the upper limit indoor air infiltration per hour (V) is 16.2m³ under 50pa pressure difference. Meanwhile, two sets of joint widths (1mm and 2mm) indicating panel assembly tightness are respectively applied to the optimized T&G joint and straight joint, then the actual air infiltration per hour (v_i) of them in the pre-set building is simulated and calculated (Table 1). According to formula 2, the "lowest sealing ratio (K_i)" of the four groups of joints can be calculated, and K_i represents the minimum ratio of the "perfectly sealed joints" in each room to meet the same Passivhaus airtight requirement.

$$K_i = (1 - \frac{V}{v_i}) \times 100\%$$
⁽²⁾

As shown in Table 1, the K_i of the optimized T&G joint is very close to that of the straight one at the lower tightness of connection (2mm width), respectively 96.4% and 97.6%, representing only 1.2% difference. However, at higher tightness of connection (1mm width), the values of both drop significantly, reaching 80.5% and 89.9%, with their discrepancy expanding to 9.4%. On the one hand, under the same airtight requirement, the lower K_i of the T&G joints indicates the joint optimization in the design stage can reduce the dependence on the construction precision and material performance to ensure the overall airtightness; on the other hand, comparing the K_i values under two joint widths, it can be seen that for building systems with higher connection tightness, the airtightness benefits brought by the optimized design of joints are more obvious. Therefore, it is of practical significance for LPBs aiming at nearly zero energy consumption.



Figure 19. The pre-set building for the airtightness simulation of optimized T&G joints and straight joints

Table 1. Relevant airtightness indicators of two types of joints.

Joint Type	Optimized T&G Joint 1mm	Optimized T&G Joint 2mm	Straight Joint 1mm	Straight Joint 2mm
Infiltration rate Q $[m^3/(s \cdot m)]$	0.64×10 ⁻³	3.43×10-3	1.24×10 ⁻³	5.09×10 ⁻³
Actual air infiltration v_i (m ³)	82.9	444.5	160.7	659.7
Lowest sealing ratio K _i (%)	80.5	96.4	89.9	97.6

4. Conclusion

To realize nearly zero energy consumption of LPBs, this paper proceeds from the airtightness of the panel joints, compares the changes of air infiltration volume of straight joints and special-shaped joints in different structural design parameters through CFD simulation and calculation, and obtains the optimized design strategy of joints. The results suggest that the air tightness of the optimized T&G joints are better than that of the conventional straight ones, and the air infiltration volume of the former can be slashed by 32.6 - 57.3%. Besides, if the goal was to meet the airtightness requirements of Passivhaus, the lower K_i values proved that a well-designed joint system would effectively cut the dependency on construction accuracy and material properties, especially for the building systems with high-performance standards.

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