Research on the Reconstruction Design of the Closed Atrium of the No. 1 Office Building of Wuhan Kaidi

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Abstract: Taking the atrium reconstruction project of the Wuhan Kaidi No. 1 office building as an example, this paper expounds on the closed atrium reconstruction project’s unique design methods. This study optimizes the atrium from the aspects of architectural aesthetics, structural stability, energy saving, and lighting performance. An asymmetric umbrella structure is used to support the atrium roof. The advantage of this umbrella structure is that the roof components are more uniform, and the atrium roof can be aesthetically “floating.” In addition, applying aluminum and glass panels at the top of the roof will directly affect the thermal and daylighting environment inside the atrium. Simulation technology realizes the trade-off design of energy consumption and daylighting index in this study. The simulation results show that the optimal comprehensive performance can be achieved when the area ratio of the glass and aluminum panels on the atrium top is 1:2. This study can provide a reference for other similar projects.

Keywords: closed atrium; reconstruction design; asymmetric umbrella-shaped structure; trade-off calculation of performance

1. Introduction

1.1. Research Objectives

Among the main points of an atrium design, the most important are structure design and performance design. This paper is based on the atrium renovation project of the Wuhan Kaidi No. 1 office building. The original building is a closed-ellipse, ring building. The project was requested to add an atrium roof to the interior of the original project. The atrium is a separate overall space for offices and meetings, with an area of 1833.95 m².

The atrium roof is located at the top of the third floor, with a minimum elevation of 12.90 m. The final structure of the atrium is an asymmetric umbrella steel structure. The structural columns are topped with tree-like forks that support the roof. The roof is a triangular steel structure with a base length and a height of about 2.4 m. The upper part of the roof is covered with glass and aluminum panels to balance the daylighting and the energy performance.

Figure 1 shows the floor plan of the building. The green and blue parts are the original building. This study will design an atrium in the red part in Figure 1.
1.2. Literature Review

Some researchers have carried out research on atrium performance optimization. Al-dawoud studied the thermal performance of different building shapes and atrium geometries under various conditions to identify the most energy-efficient atrium design [1]. Minhui and Nianping used the CFD method to study the effect of atrium size on buoyancy-driven ventilation of high-rise residential buildings and provided a theoretical basis for the design of natural ventilation in high-rise residential buildings [2]. Yuan et al. developed an artificial neural network (ANN)-based metamodel to explore multi-atrium configurations’ design approach to improve shopping malls’ energy efficiency in cold climates [3]. Ghasemi et al. tested the influence of atrium geometry on the radiation intensity of the surrounding space under overcast sky conditions in Malaysia to find the atrium with optimum geometric proportions [4]. Samant reviewed the existing studies, focusing on the influence of atrium geometry and atrium facade on the daylighting performance of the atrium and surrounding spaces to select the best glazing ratio and improve the daylighting performance of the space [5]. Sher et al. used Ecotect to explore the advantages and effectiveness of atriums in the energy performance of small buildings, taking the Azuma Row House as an example [6]. Yu et al. studied the influence of technologies such as cross ventilation, outdoor shading blinds, and floor cooling on the atrium of Groenhorst College [7]. Li et al. chose the atrium to represent one of the typical animate spaces. They adopted a pair-group analysis method to isolate and analyze a single variable and judge their influence on the building environment quality and occupant satisfaction to optimize the atrium design [8]. Li et al. used the buffer effect provided by an atrium as one typical passive strategy in sustainable building design to display the impact of the passive space on the main building space [9]. Yunus et al. evaluated the daylighting performance of atriums with different roof structures based on physical models [10]. Deng established a steady-state thermodynamic natural ventilation model in high-rise residential buildings with atrium space. Using a multi-area network method that simulates and analyzes the effects of different opening areas, locations, and transverse air flow on natural ventilation, they provided a reference basis for the ventilation analysis of atrium buildings [11]. Cui et al. proposed the optimal plan for energy-saving and natural lighting effects, which realized the energy-saving and emission reduction of the atrium and ensured a better indoor natural lighting effect [12]. Yu et al. proposed renovation measures of the solar wall to
optimize the heating design scheme through atrium measurement and CFD simulation [13]. Huang et al. used DAYSIM to analyze the influence of four parameters of the double atrium—spacing, shape, position, and area—on the daylighting performance on the first and sixth floors and found that the change of these parameters would significantly affect the lighting energy consumption [14]. Kazemzadeh and Tahbaz investigated temperature levels in atriums with and without plants, and the research showed that plants could effectively reduce the temperature [15].

There are studies on the crowd’s behavior after the renovation of the atrium, such as evacuation and satisfaction. Yan explored the humanistic design method for the atrium space of modern architecture from the aspects such as atmosphere building, ecological and energy saving, and ecological intelligence to provide effective methods for creating future atrium space [16]. Through the post-use evaluation research on the subjective satisfaction of the atrium of the Crescent Tower of Zhejiang University and the satisfaction of the physical environment, Gong et al. used a quantitative method to provide the necessary data support for the space renovation design [17]. The authors put forward four aspects of operation management of the design direction and strategy for the renovation of atrium space, summed up the application process of the existing building atrium space renovation based on post-use evaluation, and demonstrated its practical significance to the existing building space renovation. Jing and Bian studied the change of teaching mode and technical means and renovated and expanded the original building atrium of the School of Architecture, Tianjin University [18]. The old and new building spaces infiltrate, intersperse, borrow, and effectively use a long and narrow patio to make the new building. The physical environment and spatial environment of the building have been improved and upgraded, providing good material conditions for the development of the School of Architecture. Zhang et al. used the post-use evaluation system to conduct a post-use satisfaction survey on the renovation of the atrium [19]. Through the 350 questionnaires distributed to teachers and students of the whole hospital, and with the help of relevant statistical software analysis, certain conclusions were drawn to provide a reference for future reconstruction work and other similar designs.

It can be seen that the research in this area is in-depth and extensive, focusing on the specific analysis of ideal conditions or particular schemes, and the investigation has concluded how the atrium is affected by the physical environment and human factors. There are relative aspects of multiphysical environment interaction, and most scholars researched comprehensive light environment, thermal environment, and energy consumption through field tests, computer simulations, and scaled models. The light and heat environments are essential parts of the atrium design. In-depth research has been carried out on the design elements of the atrium light and heat environment. However, the intersection between the physical environment (light and thermal environment), material saving, and perceptual knowledge (structural display of architectural beauty) are not involved.

Regarding umbrella-shaped structure research, all the studies are about the center-symmetrical, umbrella-shaped structure on the plane, and the planes are circular, quadrilateral, hexagonal, and octagonal. The most studied aspect of these symmetrical umbrella-shaped structures is the tensioned membrane with umbrella-shaped structures, but the main focus is on the membrane rather than the steel structure. Zheng et al. analyzed the umbrella-shaped tensioned membrane structure’s natural vibration characteristics and focused on the design parameters’ influence on the structural model [20]. Michalski et al. presented results of the first industrial application of the fully coupled fluid-structure interaction simulation for aerodynamically sensitive membrane structures situated in a built environment [21]. Liu et al. analyzed the impact of hailstone impact load on the dynamic response of membrane structure and combined the impact load problem with the flexible structure [22]. Liu et al. obtained the dynamic response laws of the umbrella-shaped membrane structure under rainstorm, analyzed the influence of rainstorm load on the um-
brella-shaped membrane structure, and proposed suggestions for the safety and structural stability of the membrane structure [23]. Cl et al. conducted the dynamic experiments of umbrella-shaped membrane structure under hail load and software simulation to show that the analytical solutions were validated against the numerical and experimental results, which showed a good agreement [24]. Yin et al. analyzed the wind pressure distribution characteristics of the common double-umbrella-shaped and four-umbrella-shaped composite membrane structures. They studied the wind pressure distribution law of the combined membrane structure [25].

Studies of centrosymmetric umbrella-shaped structures and their construction include: Slivnik asserted that the distinction between mushroom- and umbrella-shaped structures must be made regarding how the load force is transferred from the roof to the pillar [26]. Chen et al. introduced the architectural profiling of the umbrella-shaped annular steel column that supported the swan-neck part in the Tianjin Museum and described the installation of the umbrella-shaped annular column [27]. Ding et al. presented a method for the modeling and structural design of a parallel umbrella-shaped cable-strut structure (PUSC). A calculation model of a 100 m-span PUSC is developed and optimized to verify the feasibility of the proposed method [28]. Zhang et al. used a case-based design technique to analyze the structural form efficiency, unit scale, and statistical relationships among umbrella-shaped structure morphological parameters [29] and the differences, characteristics, and applicable scales between different umbrella structure types in terms of their morphological characteristics. Due to the rising interest in the umbrella-shaped structure, Megahed and Naglaa presented recently embedded software technologies perpetrated by current practice in umbrella-shaped structures to explore the role of control strategies in responsive architecture [30]. Jaksch and Sedlak highlighted the determination of shape geometry and its unique characteristics when used in a constructional context (material thickness, joints, and bracing) [31]. Song et al. discussed the application of the umbrella-shaped structure on the roof of the central station of Fuzhou Railway Station, the roof of which adopts a composable umbrella unit structure, which is a perfect combination of structural form and architectural creativity [32]. Li and Feng adopted an umbrella-shaped steel structure support and changed the traditional steel pipe frame from the ground to the steel pipe frame from the top of the support platform, which proved that the technology had achieved good results in engineering practice [33]. According to the form and stress characteristics of the umbrella-shaped support structure, Lin et al. carried out proper segmentation. They formulated a rational hoisting sequence by combining it with the reinforced concrete structure’s construction sequence and the temporary layout road [34]. By setting an adequate installation sequence and technical measures, installation and welding are carried out without rigid support to ensure the construction period and economy.

It can be seen that the research on the umbrella-shaped structure is all based on the form being centrosymmetric. In contrast, the complex and asymmetrical umbrella-shaped design is not involved, and the structural characteristics of the umbrella-shaped system itself are not discussed, all of which are membrane structures. Therefore, this study fills this gap and expounds on the advantages of an asymmetrical umbrella-shaped structure design.

2. Materials and Methods

This study compares the two structural forms using the questionnaire survey and structural performance analysis and selects a better structural design scheme. Energy modeling and daylighting analysis obtain the optimum ratio of aluminum and glass.
2.1. Structural Design Methods

2.1.1. Structural Design Principles

In the expansion project, it is necessary to ensure that the structure of the extension part can support itself so that the extension and the original parts are independent of each other. Suppose that the two parts of the structure are not independent of each other. In that case, it is necessary to use steel reinforcement to strengthen the beams, columns, and slabs of the original building, which will affect its use. Therefore, the new part must have an independent structural system.

Since there is no structural connection between the extension and the original building, columns have to be used to support the extension. On the other hand, the number of columns should be as small as possible to ensure the integrity of the entire space while reducing the damage to the foundation. On the premise of guaranteeing the performance of the structure, columns should be clustered to save material.

2.1.2. Two Structural Design Methods and Their Comparison

This article compares the two structure types. The roof of this scheme is designed as a single-layer reticulated shell, and two structural plans can be considered. One is to keep the column structure strong while the upper part is weak and presents an asymmetrical umbrella-shaped structure; the second method is to use trusses to reinforce the single-layer mesh. The reinforced superstructure falls on the columns as a whole, reducing the rigidity and strength of the columns.

This research compares the two structures in two aspects: one is the comparison of structural properties. By comparing the two structural designs and steel consumption data, the paper shows their respective advantages and disadvantages; the other is to investigate which structural form is more welcomed through questionnaires. The best solution is given based on the comparison results of the above two aspects.

Due to the large span of the atrium (76 m × 36 m) and the giant column spacing (39 m), it is necessary to carry out forked treatment on the top of the columns of the asymmetric umbrella-shaped structure to meet the support requirements for the roof and, at the same time, show the beauty of the system. As discussed above, using branches to support the reticulated shell results in a weak upper structure, which requires pillars with solid structural strength to maintain it.

2.1.3. Analysis of Survey Questionnaire

Using questionnaires, the visual effects of the two schemes were analyzed, and the structural types recognized by users and architects were obtained.

2.2. Performance Study

The covering material of the roof is composed of glass and sandwich aluminum plates, and it is necessary to carry out the trade-off calculation of building performance indicators. The rising proportion of glass will increase the energy consumption of buildings, while the growth of the ratio of sandwich aluminum panels will not be conducive to natural lighting. This project simulates the scheme’s performance and designs the distribution of the glass and aluminum plates according to the simulation results.

The scheme is shown in Figure 2. The aluminum plate area is 1196.46 m², and the glass area is 730.49 m².
2.2.1. Analysis of Natural Lighting

Radiance is used to calculate the natural lighting illuminance value at the bottom of the atrium, and the model is shown in Figure 3.

Figure 3. Natural lighting model diagram.

2.2.2. Energy Consumption Analysis

This paper uses Design Builder to simulate the building energy consumption, analyze the energy consumption under different distributions, and optimize the design of the atrium top covers. The original building was in the shape of a ring as a whole, and the reconstructed building is to add an atrium roof on top of the third floor of the original building, which makes the original building form a closed space. Foundations different
from the original building are designed for the atrium so that the thermal performance of
the building can be calculated.

Building simulation parameters are based on the operating standards of ordinary office
buildings. The building model’s meteorological parameters are based on Wuhan. The
air-conditioning temperature of the building should be controlled at 26 °C or above in
summer. The air-conditioning temperature in winter should be directed at 18 °C or below.
The rainfall is concentrated from April to September, and the outdoor humidity is
generally high. Relevant meteorological data show that the annual average relative humidity
in Wuhan is about 75.7%. According to applicable regulations, the indoor relative humidity
is controlled chiefly at 30%–50%. Therefore, the building’s relative humidity can be set to
30%.

The building energy simulation parameters are shown in Table 1.

Table 1. Building energy simulation setting parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use density (person/m²)</td>
<td>0.1110</td>
</tr>
<tr>
<td>Heating set point temperature °C</td>
<td>18.0</td>
</tr>
<tr>
<td>Cooling set point temperature °C</td>
<td>26.0</td>
</tr>
<tr>
<td>Relative humidity set value %</td>
<td>30.0</td>
</tr>
<tr>
<td>Fresh air volume (L/s-person)</td>
<td>10.0</td>
</tr>
<tr>
<td>Indoor ventilation minimum temperature control °C</td>
<td>16.0</td>
</tr>
<tr>
<td>Power density (W/m²)</td>
<td>11.77</td>
</tr>
</tbody>
</table>

The building volume is divided into an original ring-shaped one and an internal
atrium part. The structural data of these two parts are shown in Table 2.

Table 2. Building construction parameters.

<table>
<thead>
<tr>
<th>Component Name</th>
<th>Number of Plies</th>
<th>Component Structure</th>
<th>Thermal Parameters—U Value (W/m²·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior wall of original building</td>
<td>2</td>
<td>Concrete blocks/tiles-block, mediumweight, 150 mm (150.0 mm) + Rock wool-unbonded (50.0 mm)</td>
<td>0.700</td>
</tr>
<tr>
<td>Roof of original building</td>
<td>2</td>
<td>Polystyrene (80.0 mm) + Concrete, Reinforced (with 2% steel) (120.0 mm)</td>
<td>1.453</td>
</tr>
<tr>
<td>Floor of the original building</td>
<td>3</td>
<td>Brickwork Inner (30.0 mm) + Cement/plaster/mortar-cement (20.0 mm) + Concrete, Reinforced (with 2% steel) (120.0 mm)</td>
<td>2.993</td>
</tr>
<tr>
<td>Foundation of the original building</td>
<td>3</td>
<td>Brick (30.0 mm) + Cement/plaster/mortar-cement (20.0 mm) + Concrete, Reinforced (with 2% steel) (350.0 mm)</td>
<td>2.384</td>
</tr>
<tr>
<td>Exterior Windows of the original building</td>
<td>3</td>
<td>Grand Engineering Glass 6.0low-e glass &lt;GEAB175.GRA&gt; (6.0 mm) + Air gap (12.0 mm) + TECNOGLASS SA Low-E N48/25 on Clean 6 mm &lt;6Low-E N 48-25-CL.TEG&gt; (6.0 mm) (6+12A+6 hollow LOW-E)</td>
<td>1.262</td>
</tr>
<tr>
<td>Foundation of the atrium</td>
<td>5</td>
<td>Brick (30.0 mm) + Cement/plaster/mortar-cement (20.0 mm) + Concrete, Reinforced (with 2% steel) (120.0 mm) + Polystyrene (80.0 mm) + Concrete, Reinforced (with 2% steel) (120.0 mm)</td>
<td>0.631</td>
</tr>
<tr>
<td>Roof of the outer circle of the atrium</td>
<td>5</td>
<td>Soda lime glass (including “float glass”) (6.0 mm) + Rubber (1.52 mm) + Soda lime glass (including “float glass”) (6.0 mm) + Air gap (9.0 mm) + Glass-foam at 50 °C (8.0 mm)</td>
<td>0.519</td>
</tr>
<tr>
<td>Roof of the inner circle of the atrium</td>
<td>3</td>
<td>Aluminum (5.0 mm) + Rock wool-unbonded (50.0 mm) + Aluminum (5.0 mm)</td>
<td>0.810</td>
</tr>
</tbody>
</table>
The thermal performance of the transparent envelope is shown in Table 3.

<table>
<thead>
<tr>
<th>Transparent Envelope Material</th>
<th>Solar Transmittance Ratio</th>
<th>Visible-Light Transmittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grand Engineering Glass 6.0low-e glass &lt;GEAB175.GRA&gt;</td>
<td>0.470</td>
<td>0.715</td>
</tr>
<tr>
<td>TECNOGLASS SA Low-E N48/25 on Clean 6 mm &lt;6Low-E N 48-25-CL.TEG&gt;</td>
<td>0.243</td>
<td>0.540</td>
</tr>
</tbody>
</table>

To select the optimal configuration method, the software set up three structural models of the atrium roof: all-aluminum-plate roof, all-glass roof, and aluminum-plate with glass roof. We simulated energy consumption and compared and analyzed the thermal data of the three structural forms to get the most suitable atrium roof construction design.

3. Results and Discussion

3.1. Structural Design Results

3.1.1. Comparison between the Two Structures

The advantages of the forked asymmetric umbrella-shaped structure are analyzed as follows.

First, the asymmetric umbrella-shaped structure can make the cross section of the rods required for the roof uniform. As shown in Figure 4, the stress points of the support (red points in Figure 4) are distributed as evenly as possible so that the black part of the roof can be uniform.

![Figure 4. Roof plan.](image)

Second, the asymmetric umbrella-shaped structure can also cause the columns and the roof to seem not directly connected, forming a “floating feeling” of the roof and enhancing the visual effect. As shown in Figure 5, the green is the overhanging members below the stigma, which are connected by the red cables to form an asymmetric umbrella-shaped structure. With this branched structure, the upper reticulated shell is not connected with the stigmas directly.

The asymmetric umbrella-shaped structure supports the overall single-layer roof through the “cantilever + cable” components extending from the columns to the surroundings. Since the roof is a single layer, its rigidity is slight, and the “cantilever + cable” is mainly used. The components transfer the load to the lower support columns. The bending moment load borne by the support columns is significantly increased, resulting in a large amount of steel used for the support columns. Like the umbrella or natural tree structure, the umbrella handle and the trunk occupy considerable stress materials. At the
same time, through the use of structural components such as roof (umbrella surface), sup-
port (umbrella branch), and support columns (umbrella handle), an internal use space
similar to natural trees is formed. Three large trees with intersecting branches and leaves
“grow” in the inner courtyard of the existing building, and the roof is skillfully structured
as a “shaded green space” to maximize the architectural effect.

Figure 5. Asymmetric umbrella-shaped structure.

As shown in Figure 6, the pillars of the asymmetric umbrella-shaped structure do not
touch the roof, which can create a “floating feeling” and the effect of being under the tree.

Figure 6. The floating and under-the-trees feeling of the design.

This scheme can also adopt the traditional truss structure. For example, Figure 7 is a
conventional truss structure with a weak “floating feeling”. The truss structure forms a
single-piece truss with a high spatial height by connecting the roof members and the columns and forms an evacuated grid structure with a cross truss as the primary stress system. Due to the considerable size of the roof structure and the significant overall rigidity, the bending moment produced by the lower support column is small. Therefore, the column section is small in this structural type, and the overall steel consumption is negligible. However, the roof trusses largely occupy the interior space, which cannot form a dome-shaped internal effect under the tree.

Figure 7. Truss structure.

3.1.2. Results of Steel Consumption

The amount of steel used for the asymmetric umbrella-shaped structure is 290 tons, and the amount of steel used for the truss structure is 225 tons. Compared with the asymmetric umbrella-shaped structure, the truss structure has high rigidity of the upper structure. The upper frame is directly placed on the columns. The requirements for the column are low, and the amount of steel used is saved (Figure 8). Because the rigidity of the upper cover is slight, the asymmetric umbrella-shaped structure mainly supports the upper system through branching. The components transmit the load to the lower support columns, and the bending moment load borne by the support column increases significantly, resulting in a large amount of steel used for the support columns (Figure 5).

Figure 8. Conventional truss structure.
3.1.3. Results of the Survey Questionnaire

A total of 200 valid questionnaires were collected, of which 195 selected the asymmetric umbrella-shaped structure and 5 selected the truss structure. Fifty people who chose the asymmetric umbrella-shaped structure were randomly interviewed, and 45 people chose the asymmetric umbrella-shaped structure mainly because of the visual effect. They believed that the saved steel consumption could not be realized by direct observation. Five people thought that the asymmetric umbrella-shaped structure was more organic and coordinated, the upper part of the truss structure was "chaotic", and there were too many rods.

3.1.4. Stability Analysis of Roof Structure

Because the umbrella-shaped design is finally adopted in this scheme, and the stability of the umbrella-shaped system is poor, the stability analysis of the umbrella-shaped structure is given in this part.

The design uses ANSYS software to calculate and analyze the overall stable bearing capacity of the structural system, and the mechanical model considers the structural geometric nonlinearity. The overall stable buckling value control standard: refer to the “Technical Regulation for Spatial Grid Structures” (JGJ7-2010), when the structure is analyzed in the whole process of elastic materials, the minimum stable bearing capacity coefficient is 4.2. The critical point load value that causes the structure to become unstable or collapse should be greater than the loads in a regular use state is 4.2 times. When analyzed as elastic–plastic material, the minimum stable bearing capacity factor is 2.0.

After applying the initial geometric defects according to different buckling modal distributions by the uniform modal defect method, it is found that the stable bearing capacity of this project is not very sensitive to the initial geometric defects. After analysis, the buckling mode of the overall deformation in the mid-span is selected as the initial defect distribution mode. The size of the defect is 1/300 of the span.

Figures 9 and 10 analyze the stability coefficient of the elastic state, which is used to find the weak area of the structural system’s stability performance without considering the material’s plasticity, and the safety stability coefficient to prevent the structural system from becoming unstable. Generally, the stability coefficient is controlled to be greater than five.

Figures 11 and 12 show the stability coefficient analysis of the elastic–plastic state, which is used to find the weak area of the structural stability performance considering the material plasticity to prevent the structural system from destabilizing due to the local yielding of the structural material. Generally, the stability coefficient is controlled to be greater than 2.5.

Figure 9. Elastic instability of the roof structure.
Under the elastic instability state, the bearing capacity coefficient of the roof structure can reach 14, and the unstable part occurs in the middle of the roof, which is a typical shell forking instability. In the elastic–plastic analysis, the overall deformation of the roof reaches 0.5 m, the structure has sufficient ductility, and the stable bearing capacity coefficient is 3, which meets the requirements of the specification.

3.2. **Performance Design Results**

3.2.1. Analysis Results of Natural Lighting

The natural lighting illumination is calculated for three types of atriums: all aluminum plate rooves, aluminum plates with a glass roof, and all glass rooves. The calculation
results are shown in Figure 13 and Table 4. When the aluminum plate + glass combined roof is used, the illumination standard of natural lighting is met.

![All aluminum plates](image1.png)  ![Aluminum plates and glass](image2.png)  ![All glass](image3.png)

**Figure 13.** Atrium natural lighting illuminance distribution diagram.

**Table 4.** Atrium illumination value (lux).

<table>
<thead>
<tr>
<th></th>
<th>All Aluminum Plates</th>
<th>Aluminum Plates and Glass</th>
<th>All Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average illumination</td>
<td>9.1</td>
<td>1177.5</td>
<td>4426.4</td>
</tr>
<tr>
<td>Minimum illumination</td>
<td>4.8</td>
<td>640.0</td>
<td>2800.0</td>
</tr>
<tr>
<td>Maximum illumination</td>
<td>44.8</td>
<td>2140.0</td>
<td>5600.0</td>
</tr>
</tbody>
</table>

3.2.2. Energy Consumption Analysis Results

The original building area and total building area are obtained through software statistics. The original building area is about 29,739.32 m$^2$, and the entire building area is 31,573.27 m$^2$.

The winter heating period in Wuhan is generally from 1st December to 28th February of the following year for three months, ensuring that the indoor temperature is maintained above 18 °C ($\pm$2 °C) throughout the day. Therefore, the analysis and calculation range of heating energy consumption in winter can be set from 1st December to 28th February of the following year. Because Wuhan is a hot summer and cold winter area, and the high temperature in summer is long, Wuhan starts to use air conditioners in early June and summer, and the highest temperature appears in July and August, so the use of air conditioners ends at the end of September. After relevant specifications and climate analysis, this scheme’s calculation range of cooling energy consumption can be set from June 1st to September 30th.

The hourly data of the building’s annual energy consumption are obtained through simulation. The energy consumption of the original building and different atrium roofs in the summer cooling period and winter heating period is extracted, and the annual average energy consumption per unit area of the building is calculated, as shown in Table 5.

**Table 5.** Building energy simulation results.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Original Building</th>
<th>All Aluminum</th>
<th>All Glass</th>
<th>Aluminum Plates and Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total energy consumption for heating (kWh)</td>
<td>311,282</td>
<td>399,631</td>
<td>413,629</td>
<td>402,462</td>
</tr>
<tr>
<td>Total cooling energy consumption (kWh)</td>
<td>1,359,233</td>
<td>1,475,610</td>
<td>1,579,090</td>
<td>1,507,761</td>
</tr>
<tr>
<td>Total construction area (m$^2$)</td>
<td>29,739.32</td>
<td>31,573.27</td>
<td>31,573.27</td>
<td>31,573.27</td>
</tr>
<tr>
<td>Heating energy consumption per unit area (kWh/m$^2$-year)</td>
<td>10.47</td>
<td>12.66</td>
<td>13.10</td>
<td>12.75</td>
</tr>
<tr>
<td>Cooling energy consumption per unit area (kWh/m$^2$-year)</td>
<td>45.70</td>
<td>46.74</td>
<td>50.01</td>
<td>47.75</td>
</tr>
</tbody>
</table>

It can be seen from the above table that, with the installation of the atrium, the heating energy consumption and cooling energy consumption per unit area increase, and with the rise of the proportion of the glass part on the top of the atrium, the heating energy consumption and cooling energy consumption increase.
3.2.3. Comprehensive Performance Analysis of the Scheme

It can be seen from the above analysis that, with the increase of the glass area on the top of the atrium, the total energy consumption of the building will gradually increase. However, the scheme of the all-aluminum roof cannot meet the design standard of natural lighting. Therefore, considering the two aspects of natural lighting performance and energy performance, it is appropriate to choose the atrium plates with a glass roof, which can realize the comprehensive optimization of the performance in both aspects. The simulation results show that, when the area ratio of the glass and aluminum panels at the top of the atrium is 1:2, the comprehensive optimization of energy performance and daylighting performance can be achieved.

3.3. Design Scheme

The asymmetric umbrella-shaped structure comprises steel members of different lengths, sections, and positions. The design consists of 441 nodes and 1240 rods, and 810 triangular plates, which were spatially positioned (Figure 14).

![Figure 14. Section of the umbrella-shaped structure.](image)

The low redundancy of the structure requires extremely high process requirements for the manufacture and installation of components (Figure 15).

![Figure 15. Photos of the completed project.](image)
4. Conclusions

Based on the expansion project of the Wuhan Kaidi No. 1 office building, this paper optimizes the atrium from the aspects of architectural aesthetics, structural performance, energy performance, and daylighting performance. This paper has two innovations: (1) A complex asymmetric umbrella structure is used to support the roof of the atrium. Compared with the traditional truss structure, using the umbrella structure can save 22.4% of the material consumption. In addition, the asymmetric umbrella structure can also fully display the beauty of the building, making the top structure uniform and creating a “floating feeling”. (2) The simulation technique was used to obtain the optimum ratio of the glass and aluminum panel area. The simulation results show that, when the area ratio of the glass and aluminum panels at the top of the atrium is 1:2, the comprehensive optimization of energy performance and daylighting performance can be achieved. The structural form and performance design method adopted in this paper can provide reference for other similar projects.

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