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# Numerical simulation and safety assessment of fires in historic timber structures based on fire load investigation

Xiaolie Yi[1], Shizhu Lu[1*], Yumeng Zhong[1], Jifa Zhang[1] and Yuqing Guo[1]

**Abstract**
Historic timber structures face substantial fire loads and complex fire risks. Subsequent renovations and utilization may influence their fire safety performance. Therefore, accurately predicting indoor fire development in historic buildings and assessing their fire safety performance is crucial. Numerical fire simulation is currently at the forefront of analyzing and assessing fire risks in historic buildings. However, there is a shortage of globally accessible historic building fire data. This paper proposes a method to determine fire scenarios, peak heat release rates, and development curves of indoor fires in wooden historic buildings through a fire load investigation. Using the Guangzhou ancestral hall as an example, PyroSim fire dynamics simulation software is employed to calculate fire development and assess the available safe evacuation time. The simulation results are subsequently input into the Pathfinder evacuation simulation software to ascertain the required safe evacuation time for indoor occupants. A comparative assessment is conducted to evaluate the fire safety performance before and after the renovation of historic buildings. The research findings indicate that installing closed glass curtain walls in the courtyards of ancestral hall buildings in Guangzhou accelerates the infiltration of smoke during fires, leading to rapid fire spread and long-distance ignition, significantly reducing the time available for safe evacuation. Therefore, when renovating and utilizing the ancestral hall buildings in Guangzhou, the installation of ventilation and smoke extraction systems should be prioritized to slow down fire development. Additionally, controlling the number of indoor occupants is an effective management measure to mitigate fire damage in historic buildings.

**Keywords** Fire in historic timber structure, Fire safety performance evaluation, Fire load investigation, Fire dynamics simulation, Pedestrian evacuation simulation, Fire reinforcement measures

## Introduction

Guangzhou boasts thousands of historically significant and unique architectural treasures, including ancestral halls, temples, residences, ancient towers, and a diverse array of other building types [1]. Unfortunately, historic buildings are more prone to fire risks compared to other structures due to their predominantly wooden construction and the presence of abundant combustible materials indoors [2]. Moreover, many historic buildings feature expansive attic spaces with steeply pitched roofs. This configuration hinders the escape of high-temperature smoke, increasing the risk of fire and complicating firefighting efforts. Ancestral hall buildings represent the most iconic type of historic architecture in Guangzhou, with some already designated as cultural heritage conservation units [3]. In recent years, many ancestral hall buildings have been protected, restored, and repurposed. A common practice in these renovations is to install enclosed glass curtain walls around interior courtyards. This modification approach may significantly impact the

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fire safety performance of historic buildings [4]. Once a fire breaks out, the safety of both the historic building and the occupants inside may be seriously jeopardized. Therefore, analyzing the characteristics of indoor fire smoke movement and occupant evacuation behavior after installing enclosed glass curtain walls around interior courtyards of ancestral hall buildings is crucial for evaluating the fire safety performance of historic buildings after renovation and repurposing. This analysis aids in proposing non-intrusive improvement measures to reduce human and property losses [5].

Many studies are currently focused on the risk assessment and management of building fires, with research methods shifting from qualitative and semi-quantitative approaches to quantitative research [6–9]. The Disaster Risk Index Method and Geographic Information System-based Risk Mapping Method are common qualitative and semi-quantitative assessment methods for fire risk [10, 11]. Both are large-scale static assessment methods that cannot simulate the uncertainty and dynamics of complex disaster risks [12, 13]. The subsequent development of quantitative assessment methods for building fire risks mainly includes real fire tests [14], reduced-scale fire experiments [15], and computational numerical simulations [16]. Researchers have utilized computational numerical simulation techniques to develop a series of fire numerical models, safety evacuation models, and fire risk assessment models that are widely applied internationally[17, 18]. The fire simulation field model combines computational fluid dynamics (CFD) simulations and fire combustion reaction models, allowing for a more refined analysis of changes in parameters such as fire temperature and products[19, 20]. For instance, the fire numerical simulation software PyroSim developed by the National Institute of Standards and Technology (NIST) in the United States, integrates fire dynamics simulation (FDS), the smoke visualization program Smokeview, and evacuation software [21]. Some scholars have comprehensively utilized these engineering tools to assess the fire risk and fire safety performance of buildings and proposed optimal measures for improving fire resistance performance based on numerical simulation results [22, 23]. Researchers compared full-scale indoor fire experiment data of wooden historic buildings with simulated predictive data from FDS software. The results demonstrate that utilizing PyroSim software to simulate the growth stage of indoor fires in historic buildings can accurately reflect the actual fire development situation [24].

The accuracy of numerical simulations of building fires is influenced by various factors, with the most critical being the setting of fire heat release rate, the heat value of combustible materials, and product characteristics [25]. In studies of the initial growth of fires in buildings, experimental fire models or $t^2$ fire models are generally employed based on the internal spatial characteristics of the building and the properties of combustible [26]. The four types of fire growth—slow, medium, fast, and ultra-fast—are distinguished based on the heat release rate of different combustible materials. Researchers have obtained maximum heat release rate data for common combustible materials and various fire scenarios (such as offices, supermarkets, etc.) through extensive fire experiments. Based on this data, they have designed fire development curves. These curves are widely used in numerical simulation and analysis of building fires, providing crucial data support for fire safety research. Several studies [27, 28] have simulated fire dynamics to recreate fire scenes and investigate the characteristics of fire spread and smoke movement. These studies collectively demonstrate the accurate prediction of fire development and smoke movement through fire simulation.

In our view, current fire simulation research primarily focuses on modern architectural areas, while there is relatively little research on fire simulation in historic buildings [17, 29, 30]. It is worth noting that most of the heat release rate settings used in fire research are based on fire safety regulations or literature references for modern buildings. This approach may lead to a significant underestimation of the scale of fires in historic buildings. Few countries, aside from the United States, have established standard values for the peak heat release rate of historic buildings [31, 32].

Fire load surveys represent an essential method for understanding the indoor fire risk of historic buildings, with several researchers having undertaken relevant investigations. A fire load density survey for historic buildings in Brazil revealed an average density of 2989 $MJ/m^2$, with wood constituting 35% of the mobile fire load and 37% of the fixed fire load [33]. The recorded figures exceeded the Brazilian standard NBR 14432 by tenfold. Li et al. [34] conducted a survey and statistical analysis of fire loads in 83 historic buildings in Beijing, revealing an average load of 2847.7 $MJ/m^2$. The proportion of fixed load exceeded 92%, highlighting significant disparities from modern buildings. While it is theoretically challenging to establish a relationship between indoor fire heat release rate and fire load, there is an empirical correlation between the peak heat release rate of well-ventilated indoor fires and fire load density [35]. In the case of well-ventilated indoor fires in historic buildings with a single type of combustible material (primarily wood with consistent combustion heat), the peak heat release rate and fire development curve can be estimated from the combustible mass loss rate [36].

This study aims to develop a fire design method suitable for historic wooden buildings in Guangzhou. By analyzing fire load survey data, we estimate the fire scale and development process of these wooden structures. Using the ancestral halls in Guangzhou as a case study, we apply this fire design method along with fire dynamics simulation software and evacuation simulation software to evaluate and compare the impact of installing enclosed glass curtain walls in internal courtyards on fire safety performance. Based on the findings, We propose non-intrusive improvement measures. The results will provide guidance and reference for fire numerical simulation, risk assessment, and management of historic wooden buildings in Guangzhou. Additionally, this study offers a fire performance-based evaluation method for the renovation and adaptive reuse of historic buildings, contributing to their fire protection.

## Methods and materials

The research process can be represented by a simple flowchart (Fig. 1). First, a survey of historical building fire loads and process the recorded data digitally is

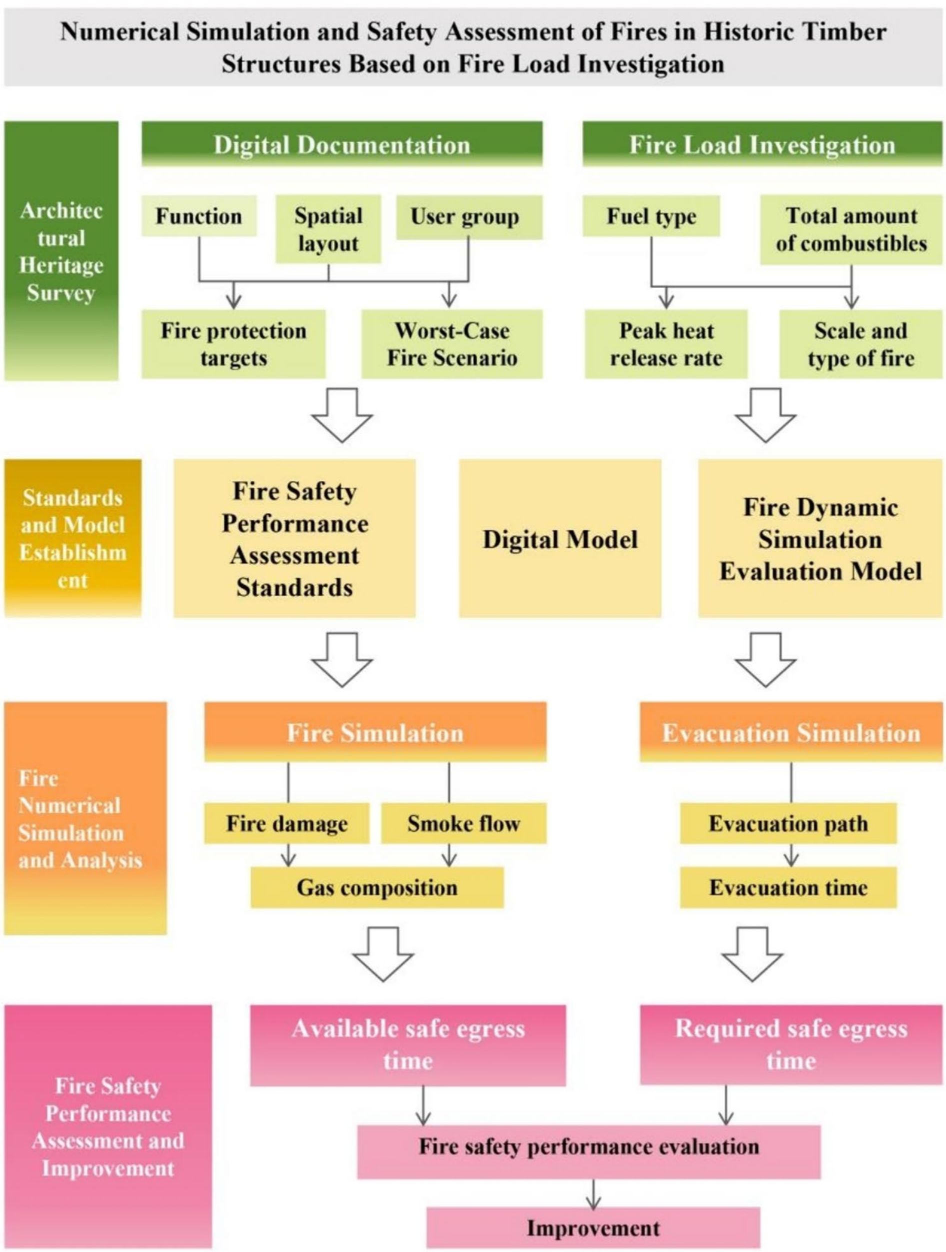


**Fig.1** Flowchart of the methodology employed in this study

conducted. Fire scenarios are then designed, including estimating the rate of heat release and the extent of the fire. A simulation model of the fire dynamics is then created using the PyroSim software. The results of the numerical fire simulation are then used in the Pathfinder evacuation model to evaluate the safety evacuation performance of the existing routes and exits. Finally, improvement measures are proposed based on the evaluation results.

## Case study

The surveyed historic building, known as the Qingyun Academy, was built in the 38th year of the Kangxi reign during the Qing Dynasty. It is located within the historic and cultural district of Beijing Road in Guangzhou and is currently listed as a cultural heritage conservation unit by the Guangzhou government. The Qingyun Academy adopts the common layout of ancestral hall buildings in Guangzhou, oriented from north to south, with a width of approximately 12.7 m and a depth of about 36.4 m across three sections [37]. It consists of three independent buildings arranged along the central axis: the front hall, middle hall, and rear hall, all featuring pitched roofs in the Lingnan architectural style (Fig. 2). Connecting corridors run along the front and back of the buildings, forming two rectangular courtyards inside without partition walls. The Qingyun Academy is one of the early examples in Guangzhou where restored ancestral hall buildings have been repurposed for public cultural services. Extensive renovations and transformations were carried out while preserving the original appearance. The primary renovation measures included enclosing the originally open courtyards with transparent glass curtain walls and dividing the space into areas such as a cafe and exhibition hall, creating conditions for the use of air conditioning and ventilation systems (Fig. 3).

## Fire load investigation and fire scenario design

Building fire load is an important indicators to assess fire hazards [38], usually reflected by the magnitude of the building fire load density, which indicates the severity of potential indoor fires. According to the calculation formula for fire load density, we can survey and record spatial data of historic buildings and the total amount of combustible materials indoors, based on the combustion heat value of building materials. By tallying the total heat value of combustible materials, we can then calculate the building fire load density [39].

$$q_m = \frac{\sum M_i q_i}{A_F}$$

where $q_m$ denotes the fire load density, $M_i$, (i = 1,2,...) denotes the mass of combustible material indoors, $q_i$ denotes the combustion heat value of combustible material per unit mass, and $A_F$ denotes indoor horizontal ground area.

The size of the building fire load density is positively correlated with the fire duration and the rate of fire growth [40]. Generally, when the fire load density is less than 1140 MJ/m$^2$, the rate of fire growth falls between slow and medium; when the fire load density ranges between 1140 MJ/m$^2$and 2280 MJ/m$^2$, the rate of fire growth lies between medium and fast; and when the fire

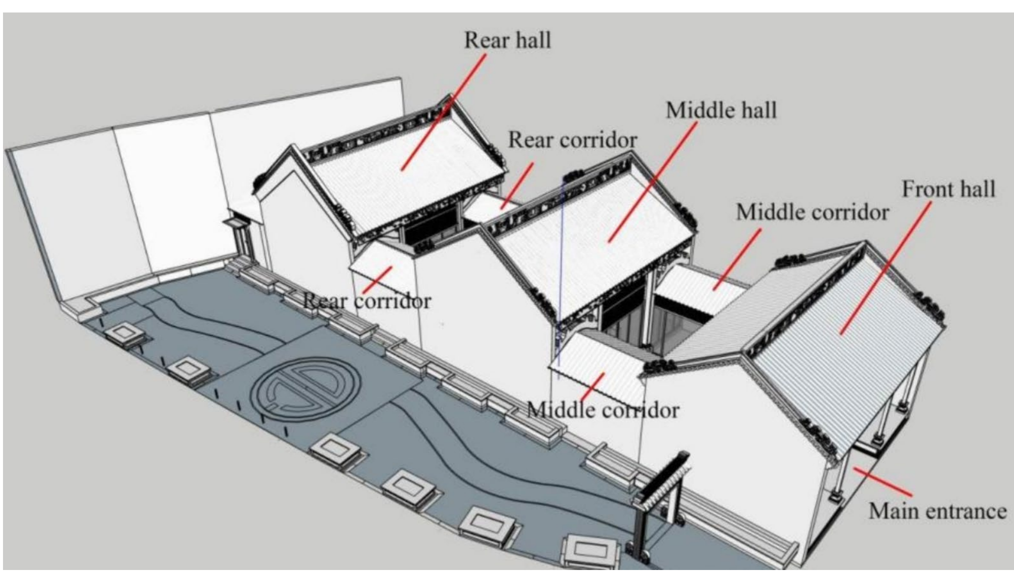


**Fig.2** The overall architectural layout of Qingyun Academy (Source: Own illustration)


**Fig.3** Qingyun Academy's indoor renovation and utilization involves enclosing the courtyard with glass curtain walls (Source: Own illustration)

load density exceeds 4560 MJ/m$^2$, the rate of fire growth can be considered as ultra-fast [41, 42].

To address the complexity and large quantity of wooden structural components in Guangzhou ancestral hall buildings, we employed digital information recording methods for the fire load survey. Firstly, we conducted on-site surveys and mapping, analyzing potential combustibles and unfavorable fire scenarios. We generated the overall floor plan of the building, as well as individual building's floor plans, elevations, cross-sections, and detailed drawings of specific structures and artistic components. Next, based on the survey drawings, we established full-scale three-dimensional models, incorporating the distribution of structural elements, decorations, and combustibles within the building interiors. Subsequently, we recorded and measured combustible materials inside the historic buildings, determining their names, quantities, and types. For small combustibles such as furniture and items, we directly measured their mass using electronic scales. For fixed combustibles that were inconvenient to measure directly, such as columns and beams, we measured their dimensions and categorized them in the three-dimensional model of the building. Their masses were calculated based on the volume of the components. Finally, we calculated the fire load density of individual ancestral hall buildings and evaluated the most unfavorable fire scenarios.

Based on the statistical data from the combustible materials survey of the Qingyun Academy as shown in Table 1, the building's wooden structural material is pine wood, with a density of $0.5 \times 10^3$ kg/m$^3$ and a combustion heat value of 19.12 MJ/kg. Among the three hall buildings, the middle hall has the highest total fire load and fire load density, with a total fire load of 218,542 MJ and a

**Table 1** Fire load statistical results for Qingyun Academy. (Source: Own calculations)

| Unit | Area ($m^2$) | Fixed fire load (MJ) | Movable fire load (MJ) | Fire load (MJ) | Fire load density ($MJ/m^2$) | Peak heat release rate (MW) | Fire patterns | Fire development coefficient ($kW/s^2$) |
|---|---|---|---|---|---|---|---|---|
| Front hall | 101.6 | 170,263.6 | 9177.6 | 179,441 | 1766 | 19.3 | Medium fire | 0.0117 |
| Middle hall | 106.7 | 10,430 | 1000 | 218,542 | 2048 | 24 | Fast fire | 0.0469 |
| Rear hall | 114.3 | 8085 | 1330 | 180,015 | 1483 | 19.4 | Medium fire | 0.0117 |

**Table 2** Relationship between fire load density and duration of fire [40]

| Fire load density ($MJ/m^2$) | 450 | 675 | 900 | 1350 | 1800 | 2700 | 3600 |
|---|---|---|---|---|---|---|---|
| Duration of fire (h) | 0.5 | 0.7 | 1.0 | 1.5 | 2.0 | 3.0 | 4–4.7 |

fire load density of 2048 $MJ/m^2$. Under conditions where building ventilation is good and oxygen supply is sufficient, the fire can last for up to 2 h (Table 2).

In theory, for the same type of combustible materials, once we have the mass burning rate and total heat value of combustible materials in heritage building fires, we can calculate the peak heat release rate of the fire, which represents the maximum heat release rate during fire flashover. The heat release rate of a building fire is defined as the total heat released by the combustion of all combustible materials inside the building per unit time [30]. The calculation formula is as follows:

$$Q = \varphi \dot{m} \Delta H$$

where $Q$ denotes the fire heat release rate, $\varphi$ denotes the combustion efficiency factor which reflects the extent of incomplete combustion of combustible materials. In various fire scenarios and ventilation conditions, the combustion efficiency factor ranges between 0.3 and 0.9. $\dot{m}$ denotes the combustible material mass burning rate, $\Delta H$ denotes the total heat value of combustible materials.

Based on the fire load survey statistics, the fire in the middle hall of the Qingyun Academy is considered the most dangerous and unfavorable fire scenario that could occur. Assuming excellent ventilation conditions at the fire scene and a combustion efficiency factor of 0.9, all combustible materials within the building are assumed to burn completely. With the average mass burning rate of reference building wood set at $0.1077 \times 10^3$ kg/s, the calculation yields a peak heat release rate of $24 \times 10^3$ kW using the formula. Thus, under ideal conditions, the peak heat release rate of the fire in the middle hall is estimated to be 24 MW. The fire load density in the middle hall is 2048 $MJ/m^2$, with a fire growth rate classified as fast and a fire development coefficient of 0.0469 $kW/s^2$. The fire model for the middle hall employs a $t^2$ fire to describe the

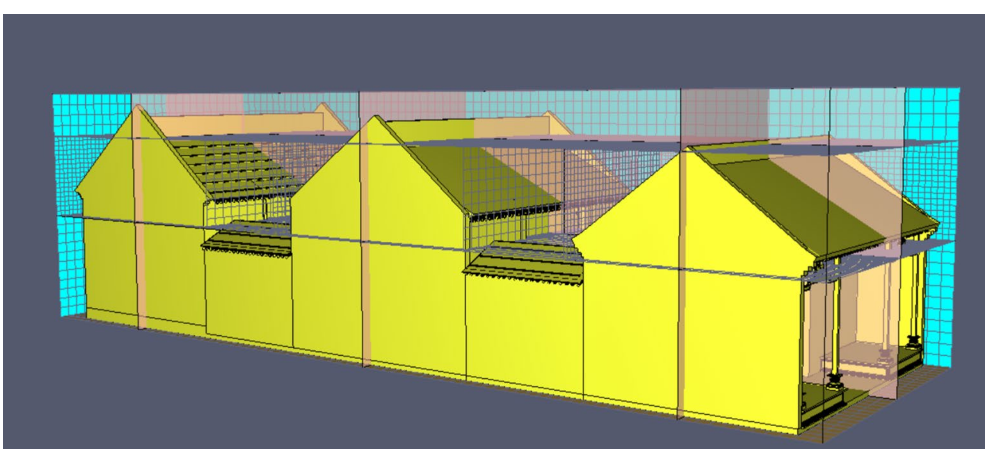

**Fig.4** The calculation area and grid division for the fire simulation model. (Source: Own illustration)

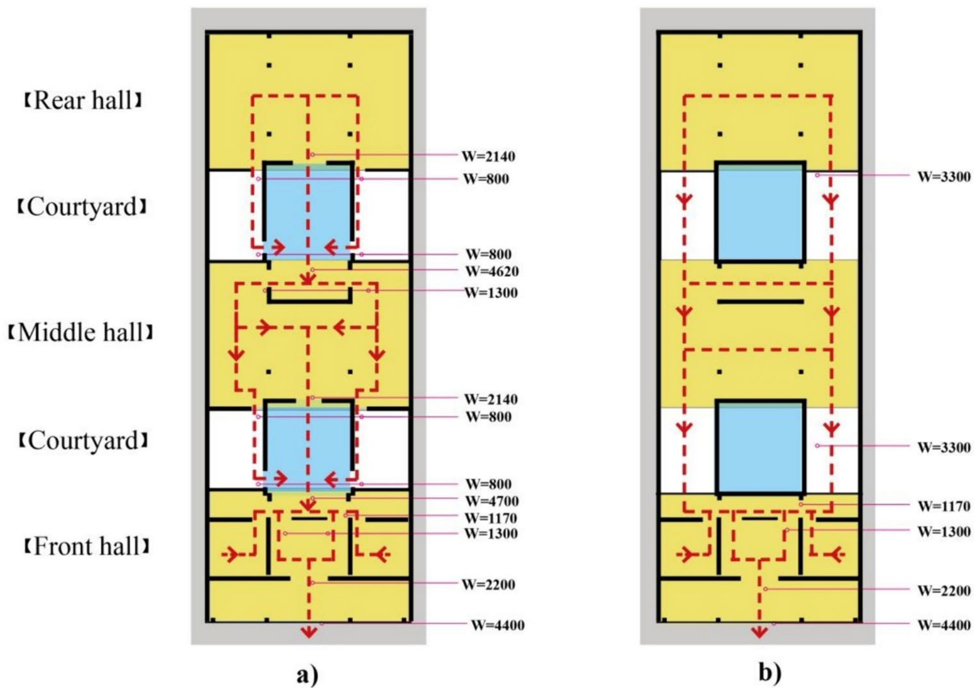


**Fig.5** Evacuation routes and corridor widths under various conditions: **a** Condition one; **b** Condition two (Source: Own illustration)

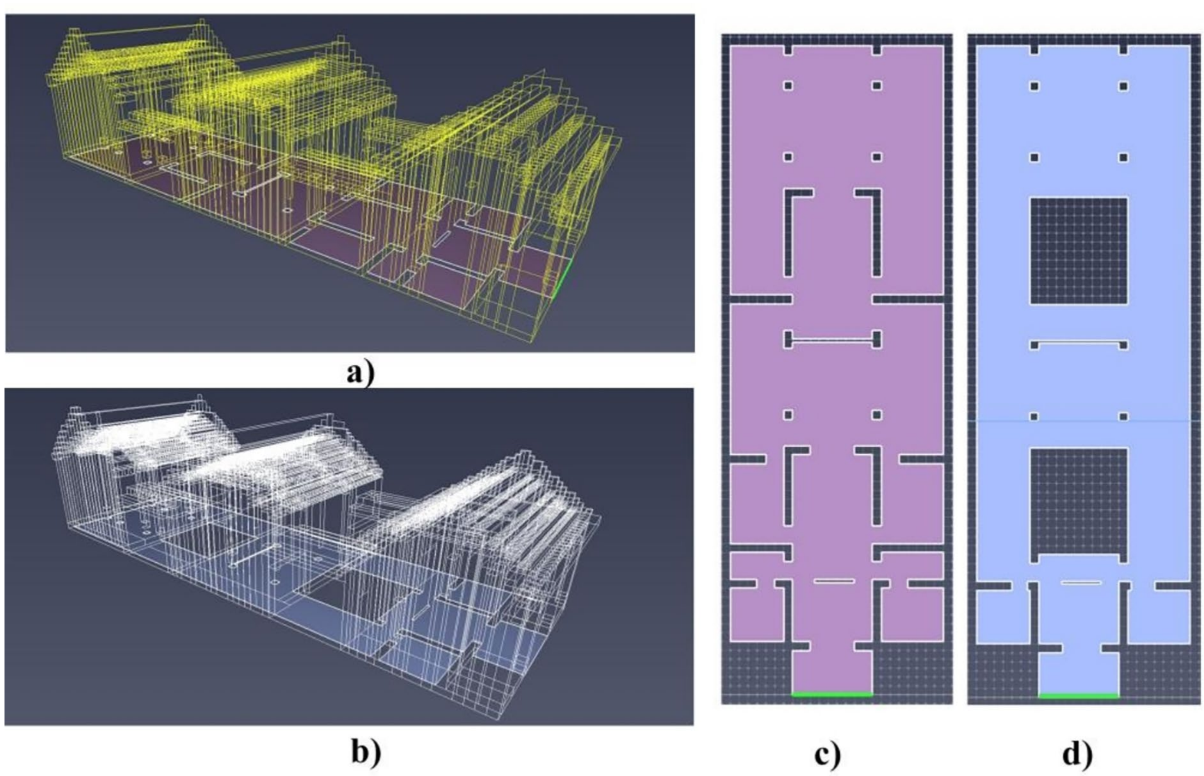


**Fig.6** Evacuation simulation model: **a** Condition one model; **b** Condition two model; **c** Evacuation space for condition one; **d** Evacuation space for condition one (Source: Own illustration)

fire development process, and the calculation indicates that it takes 715 s for the fire in the middle hall to progress from the initial stage to the peak heat release rate stage.

## FDS modelling and simulation settings

To contrast the impact of different forms of enclosed glass curtain walls on the development of indoor fires in the Qingyun Academy's internal courtyards, we established two distinct scenarios. The key difference between these scenarios is whether occupants can evacuate through the courtyard in case of a fire. Using SketchUp software, we constructed models for fire simulation, incorporating information on building grounds, walls, wooden structures, doors, windows, roofs, and other components. Subsequently, we imported these models into PyroSim software. It's important to note that the models were not set up to simulate material combustion and pyrolysis reactions but rather to reflect the influence of internal structures on the flow of fire smoke.

The computational domain for fire simulation encompasses the entire Qingyun Academy premises, extending 1 m outward from the boundaries of facade openings. The top boundary of the computational domain is positioned more than 1.5 m above the roof ridge to facilitate smoke flow. The dimensions of the computational domain in the X, Y, and Z directions are 13.5 m, 39 m, and 11 m, respectively. Except for the bottom, the remaining boundaries of the computational domain are set as open boundaries. The simulation environment maintains a temperature of 20 degrees Celsius, a pressure of $1.01\times10^5$ Pascals, and a wind speed of zero. Based on the heat release rate of pine wood combustion, the characteristic diameter of the fire source is calculated to be 0.504 m. Considering the dimensions of the wooden structural components inside the Qingyun Academy, a grid size of 0.1 m, which is 1/5 of the fire source characteristic diameter, is chosen for the key fire area, namely the roof wooden framework area. The grid size for the remaining areas is set to 0.2 m to meet the accuracy requirements of fire simulation [43, 44]. The total number of grids is 428,064 (Fig. 4).

The combustion chemical reaction used in the simulation calculation is based on the WOOD-PINE setting in the software database, representing pine wood as the combustible material. A single-step combustion reaction using a mixture fraction model is employed. The specified heat release rate per unit mass is $19.12\times10^3$ kJ/kg, with a carbon monoxide yield of 0.004 and a smoke yield of 0.015. The ignition surface is set in the middle of the middle hall, with a geometric fire source size of 1 m×1 m×1 m, and its top surface is designated as the burner. The heat release rate per unit area is set to $21.3\times10^3$ kW/m$^2$, with a surface temperature of 500℃. The chosen fire model is $t^2$, with a growth time of 715 s, after which the fire reaches a steady state. Longitudinal temperature cross-sections along the axis of the ancestral hall building and transverse temperature cross-sections for each hall are set in the model. Smoke mass fraction is set to be visible to reflect the flow of smoke within the building during the fire. After the simulation calculation, Plot3D data is outputted, including volume fractions of carbon monoxide, carbon dioxide, and oxygen, as well as smoke visibility and temperature, which will be inputted into the Pathfinder evacuation simulation software for further analysis.

## Evacuation modelling and simulation settings

In both fire simulation scenarios for the Qingyun Academy, the evacuation routes lead to the front hall as the sole exit, with a straight-line evacuation distance from the rear hall to the front hall measuring 36.4 m. According to the Chinese Fire Protection Design Code for Historic Buildings, for single-story historic buildings with a fire resistance rating of level four and no sprinkler system installed, when commercial functions are introduced internally, the maximum straight-line distance from internal rooms to the nearest safe exit should not exceed 15 m. It can be observed that under the current building fire safety regulations, the fire evacuation distance in the Qingyun Academy does not meet the requirements. This poses a fire safety design dilemma faced by many ancestral hall buildings when repurposing their usage. In scenario one, the minimum width of evacuation pathways in

**Table 3** Evacuee physical characteristics and average walking speeds. (Source: Own calculations)

| Type | Children | Youth | Young men | Young women | Middle-aged men | Middle-aged women | Elderly |
|---|---|---|---|---|---|---|---|
| Shoulder Width (cm) | 38.0 | 40.0 | 42.0 | 39.7 | 41.5 | 38.7 | 40 |
| Average Walking Speed (m/s) | 0.90 | 1.10 | 1.51 | 1.45 | 1.47 | 1.39 | 1.00 |
| Proportion (%) | 5 | 10 | 20 | 20 | 20 | 20 | 5 |

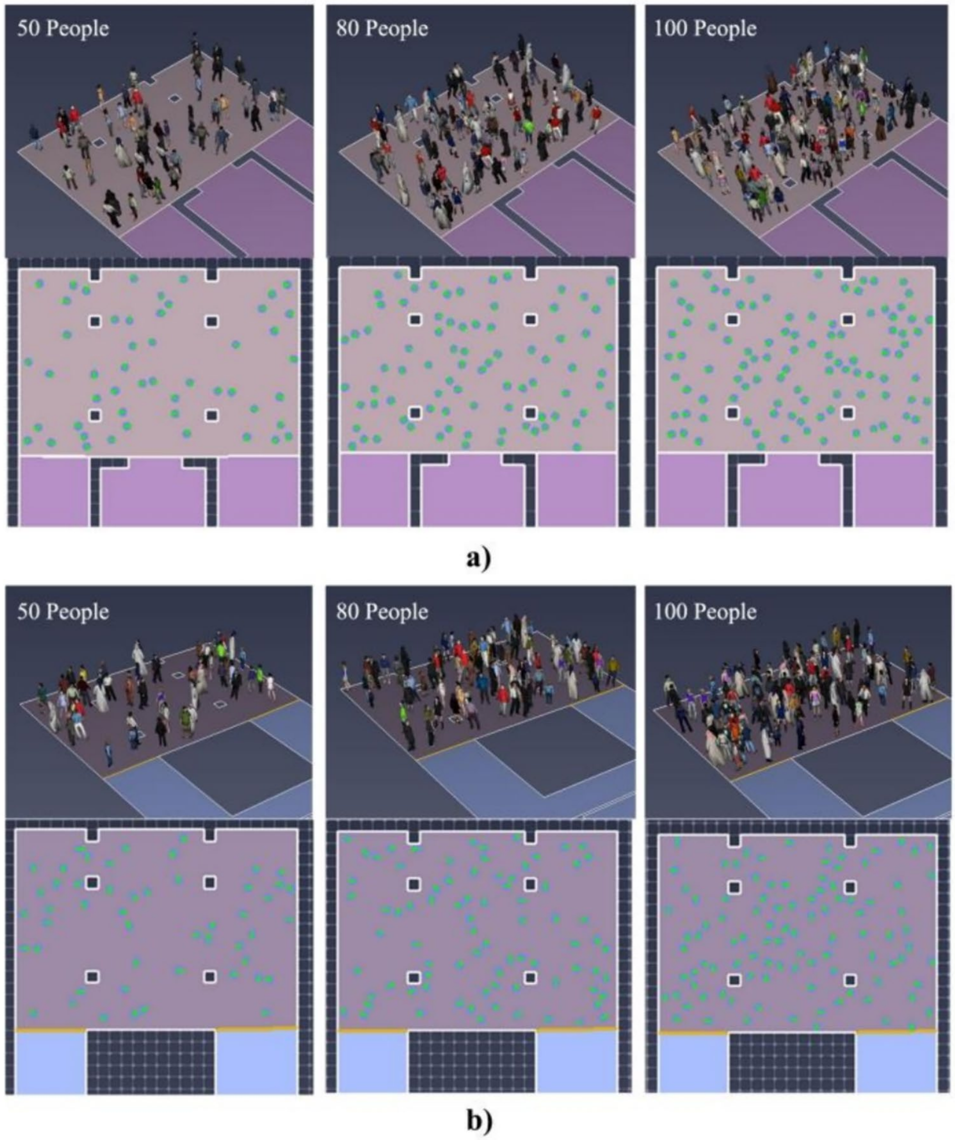


**Fig.7** Number and distribution of personnel in the rear hall under the most adverse evacuation conditions: **a** Condition one; **b** Condition two. (Source: Own illustration)

the evacuation routes is 800 mm, falling short of the regulatory minimum width requirement of 900 mm. However, in scenario two, the minimum width of evacuation pathways in the routes is 1170 mm, meeting the regulatory standards (Fig. 5).

The indoor personnel evacuation simulation for the Qingyun Academy utilizes Pathfinder, a behavior-based evacuation modeling software [45]. Pathfinder discretizes the architectural space into fine-grained grids and describes individual evacuation behaviors using the Steering mode. This model comprehensively considers the impact of architectural space and fire development on evacuation, accurately predicting individual characteristics of evacuees and their chosen evacuation routes [46]. Pathfinder is compatible with PyroSim's FDS simulation results and Plot3D smoke visualization data [47]. The evacuation simulation first imports models of different scenarios into the Pathfinder software and defines the building floor. The interior of the ancestral hall is treated as a single room, with boundaries reflecting walls, doorways, and obstacles (Fig. 6). The internal capacity limit for personnel in the Qingyun Academy is based

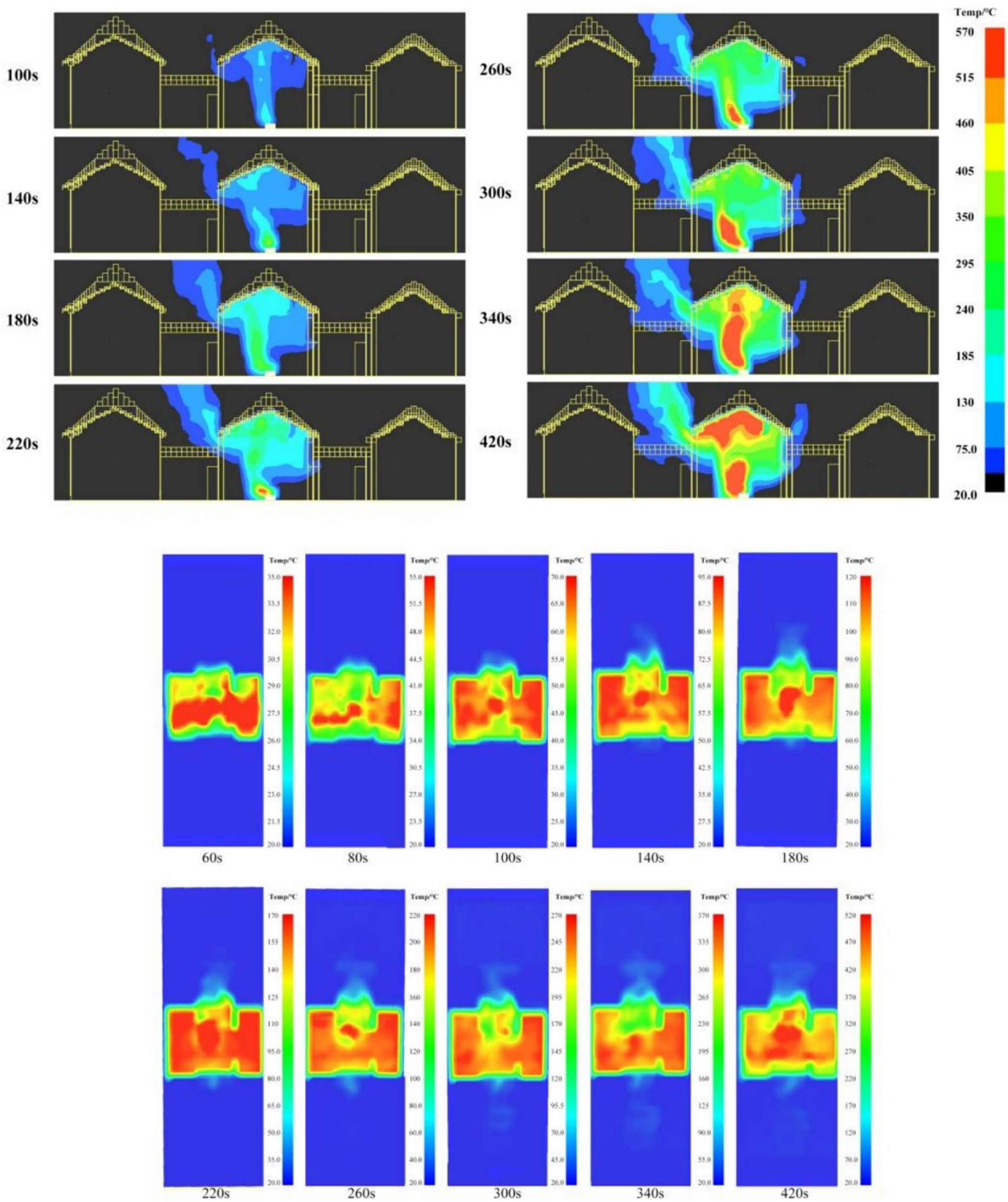


**Fig.8** Longitudinal and horizontal slice temperature under condition one (Source: Own illustration)

on the evaluation criteria for visitor capacity of Chinese cultural heritage sites, setting a minimum of $\geq 1\ m^2$/person for each individual building within historic structures, resulting in an internal capacity limit of 100 people [48]. Therefore, the evacuation simulation calculates evacuation times for different numbers of people, such as 50, 80, and 100 individuals, to analyze the relationship between fire hazard and internal personnel capacity. The simulation considers seven categories of personnel (Table 3), with body size equivalent to a cylinder with a

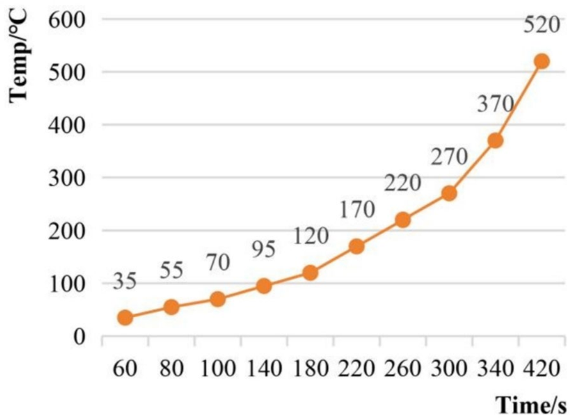


**Fig.9** Temperature rise curve of the middle hall fire scene under condition one (Source: Own illustration)

diameter equal to the shoulder width. It assumest all personnel are located in the rear hall, simulating the most adverse evacuation scenario (Fig. 7).

## Results and discussion

### Temperature changes in building fires and areas of fire damage

In scenario one of the fire simulation at Qingyun Academy, longitudinal and transverse temperature profiles at different time points are illustrated in Fig. 8, depicting the evolution of the fire and its influence. By 100 s, smoke has filled the upper roof space of the central hall and begun to escape outward through the atrium glass curtain wall doorways. At 420 s, the temperature of the upper smoke layer in the central hall reaches 570 °C, indicating a state of flashover, although the fire does not spread to the front hall or rear hall. The temperature rise curve of the central hall fire shows a continuously accelerating heating rate. By 140 s, as the smoke layer descends, temperatures in the upper smoke layer can reach 95 °C, impacting indoor personnel evacuation. When the smoke layer height exceeds the average eye level (1.7 m), and temperatures above it range between 180 °C and 200 °C, radiant heat levels below the smoke layer approach human tolerance limits [49]. With the fire temperature exceeding 180 °C, the tolerable time for evacuating personnel does not exceed 1 min. According to the fire simulation results, at 220 s, the upper smoke layer temperature in the middle hall fire scene surpasses 180 °C, indicating that the available evacuation time before reaching human tolerance limits is 220 s (Fig. 9).

Scenario two of the fire simulation at Qingyun Academy involves fully enclosing the atrium with glazed curtain walls. Longitudinal and transverse temperature profiles at different time are depicted in Fig. 10, llustrating the fire's propagation and the expanding impact of high-temperature smoke. At 140 s into the fire, high-temperature smoke begins to hinder personnel evacuation from the rear hall. By 180 s, the temperature of the upper smoke layer in the middle hall exceeds 180 °C, limiting evacuation time before reaching human tolerance limits to 180 s. At 380 s, smoke temperatures surpass 160 °C, capable of igniting the wooden roof trusses in the rear hall and facilitating fire spread. By 420 s, the highest temperature at the entrance hall reaches 90 °C, although it has not yet ignited wood, it poses significant risks to evacuating personnel. The ancestral hall's double-pitched roof design causes smoke to accumulate at the ridge and eaves after rising (Fig. 11).

### Height and visibility of the smoke layer in building fires

Smoke layer height, temperature, and visibility are important safety indicators influencing personnel evacuation during a fire. Evacuation time constraints are determined by whether the smoke layer exceeds eye level (1.7 m) and if smoke temperatures reach 180 °C to 200 °C. Even when the smoke layer is below eye level, temperatures between 110 °C and 120 °C still pose significant danger [50]. Smoke visibility plays a crucial role in determining evacuation routes. Ideally, the maximum tolerable light density should not exceed 0.2, and visibility should not fall below 5 m. When smoke visibility along evacuation routes is drops below 3 m, 30% of evacuees typically opt for alternative paths. Reduced visibility also slows down the walking speed of evacuating personnel, dropping from the normal 1.2 m/s to 0.3 m/s when visibility is less than 5 m [51].

In fire simulation scenario one at Qingyun Academy, analysis of smoke mass fraction and visibility over time reveals that initially, due to open doorways in the glass curtain walls of the central hall, smoke movement remains confined within the hall for the first 300 s after the fire begins (Fig. 12). The smoke layer descends to below head level in the crowd by 220 s, coinciding with visibility dropping below the tolerable 5 m for evacuating personnel inside the central hall, although the smoke impact area remains relatively small. By 420 s, the reduction in light caused by smoke significantly slows down the evacuation speed of personnel.

In fire simulation scenario two at Qingyun Academy, analysis of smoke mass fraction and visibility over time indicates a rapid increase in smoke movement (Fig. 13). By 180 s, the smoke layer in the central hall descends below head level among the crowd, and by 220 s, it reaches eye level at the door. By 260 s, the indoor space is filled with fire smoke, with a significant amount spilling out from the head door entrance. At 220 s, visibility in both the central hall and the rear hall drops below

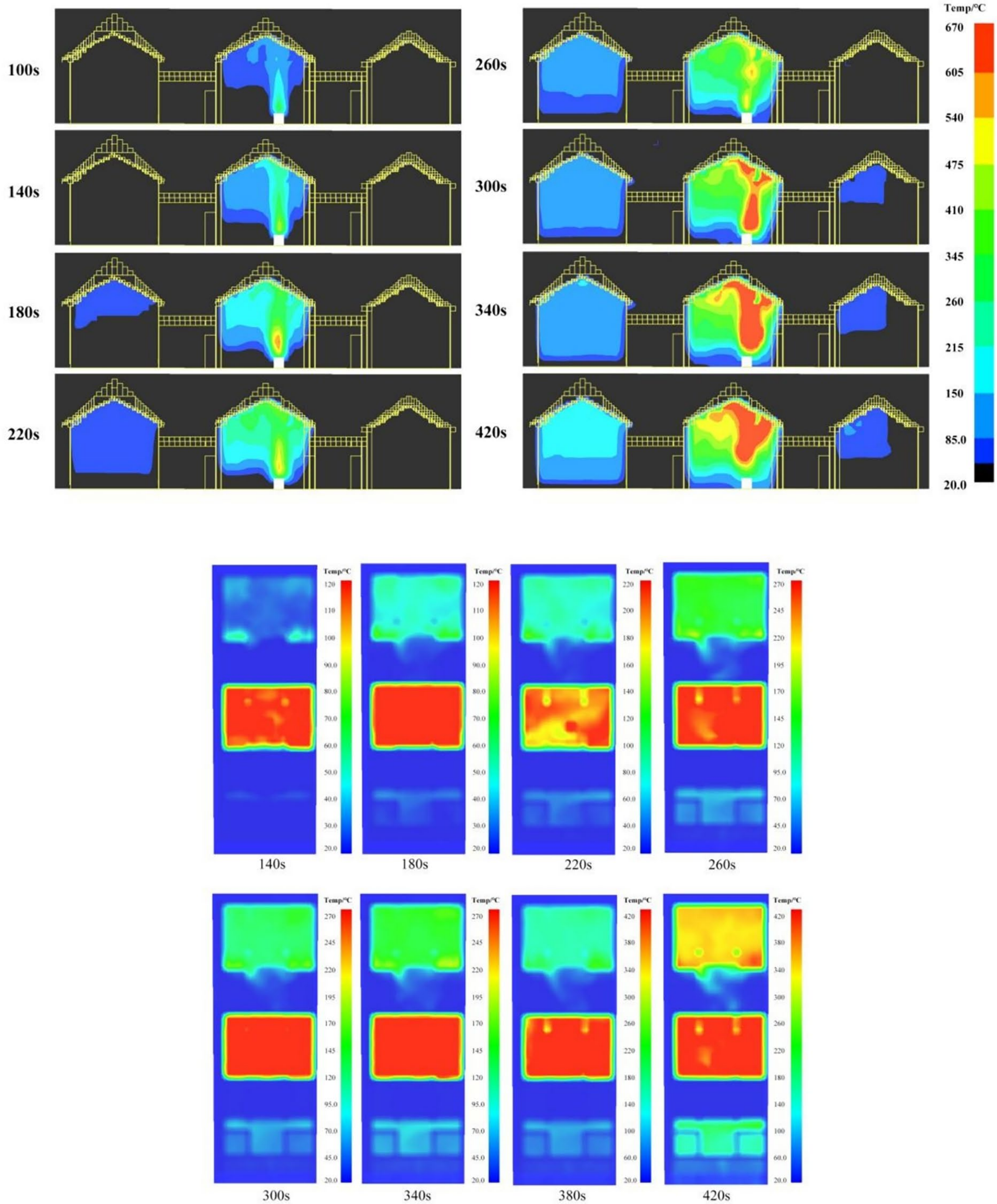


**Fig.10** Longitudinal and horizontal slice temperature under condition two (Source: Own illustration)

4.5 m, significantly slowing down evacuation speed due to reduced light caused by the smoke.

#### Changes in gas composition in building fires

The concentration of toxic gases in fire smoke, particularly carbon monoxide (CO), is a critical factor that poses a serious threat to the safety of indoor occupants

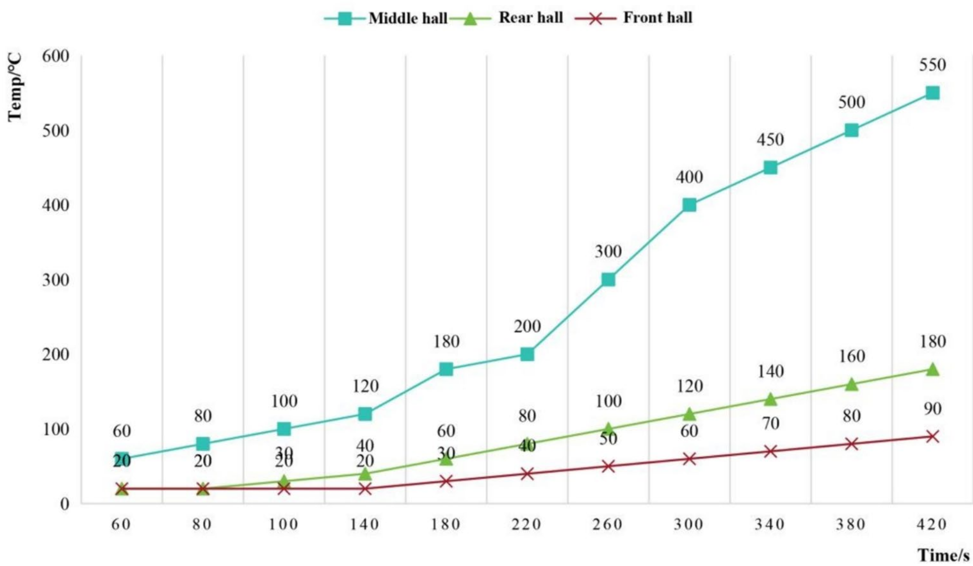


**Fig.11** Temperature rise curve of the Qingyun Academy fire scene under condition two (Source: Own illustration)

[52]. The volume fraction of CO in the fire scene serves as an indicator of smoke toxicity. When CO concentration in smoke reaches 1%, occupants indoors face potential death within 1 to 2 min. At 0.5% concentration, suffocation can occur within 20 to 30 min. A concentration of 0.1% causes discomfort within approximately 1 h, whereas levels below 0.05% have minimal effects on occupants within the same timeframe.

In fire simulation scenario one at Qingyun Academy, analysis shows that as the fire in the central hall reaches a critical state, the volume fraction of carbon monoxide reaches 0.035%. This level does not exceed the human tolerance limit and has minimal impact on indoor personnel within one hour (Fig. 14). However, significant changes are observed in fire scenario two. By 420 s, the maximum volume fraction of carbon monoxide in both the central hall and the rear hall reaches 0.04%, surpassing the human tolerance limit.

In conclusion, the design of enclosed glass curtain walls in the courtyard of Qingyun Academy significantly influences the development and hazards of fires. Comparative analysis of fire simulations reveals distinct variations in fire temperature, smoke layer dynamics, visibility, and toxic gas composition within the fire scene. The Available Safe Egress Time (ASET) for both fire scenarios is detailed in Table 4.

### Evacuation results

In Scenario one of the evacuation simulation, the total evacuation times for indoor evacuees are 55.5 s, 66.5 s, and 72.3 s for 50, 80, and 100 evacuees, respectively (Fig. 15). Evacuees predominantly choose pathways through the central hall, favoring the shortest routes, while fewer opt to pass through the courtyard. However, internal functional subdivisions such as screens, pillars, and partition walls often create narrow passages indoors, leading to congestion and increased waiting times during evacuation. As the number of evacuees rises, so does the corresponding waiting time.

In Scenario two of the evacuation simulation, the total evacuation times for indoor evacuees are 54.0 s, 75.8 s, and 77 s for 50, 80, and 100 evacuees, respectively (Fig. 16). Due to the absence of complex spatial subdivisions indoors and the decision not to use the courtyard for evacuation, the evacuation paths are generally similar. Evacuees initiate their evacuation from the rear hall, proceed through the corridors on both sides of the central hall, and ultimately reach the main entrance. However, evacuees encounter a bottleneck between the screens at the main entrance and the rear glass curtain wall, significantly slowing their progress. Despite an increase in the number of evacuees, the overall evacuation times show minimal variation.

### Evacuation safety evaluation

Based on the evacuation simulation results, the Required Safe Egress Time (RSET) is calculated considering different scenarios and indoor occupancy levels. Assuming the use of common point-type smoke detectors and a fire automatic alarm system in Qingyun Academy, the perception time for occupants $T_1$ is 40 s, the reaction time $T_2$ is 60 s, and the safety factor for evacuation movement

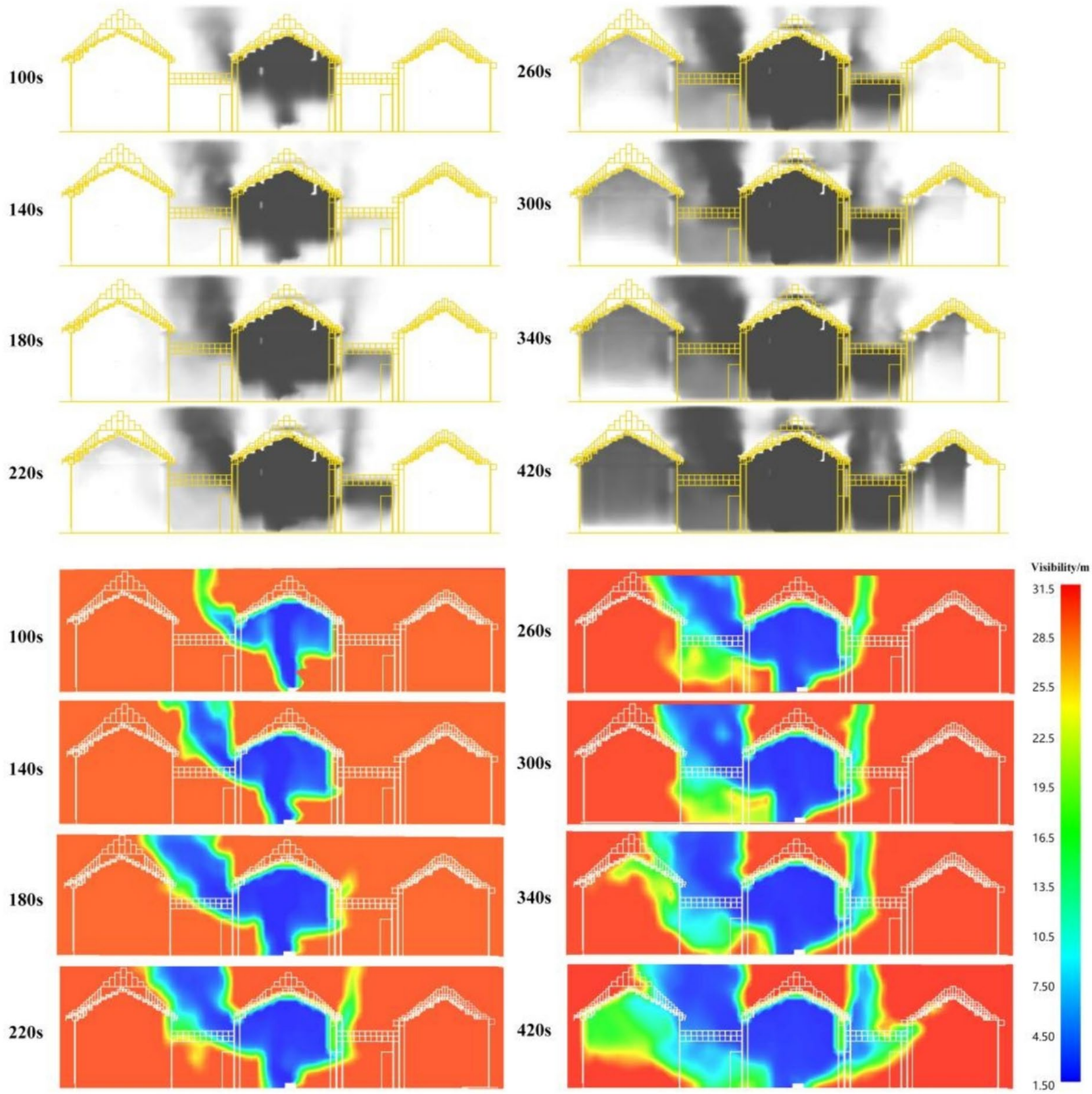


**Fig.12** Smoke flow and smoke visibility under condition one (Source: Own illustration)

time $T_3$ is 1.5. The RSET for different simulation scenarios and indoor occupancy levels is shown in the Table 5.

$$\text{RSET} = T_1 + T_2 + k \times T_3$$

where $T_1$ denotes the perception time for occupants, $T_2$ denotes the reaction time, $T_3$ denotes the evacuation movement time, $k$ denotes the safety factor.

The impact of indoor evacuation population on safety requirements at Qingyun Academy varies significantly between the two fire scenarios. In scenario one, evacuation meets safety standards regardless of whether there are 50, 80, or 100 people. Despite the presence of numerous interior compartments causing longer passage through the central hall, the open doorways in the atrium's glass curtain wall facilitate early venting of fire smoke through the atrium, thereby extending the available evacuation time. Conversely, in scenario two, safety evacuation requirements cannot be met when the indoor population exceeds 50 people. This is due to the complete closure of the atrium in this scenario, which renders it unusable as an evacuation route, resulting in a rapid decrease in indoor smoke layer height and consequently

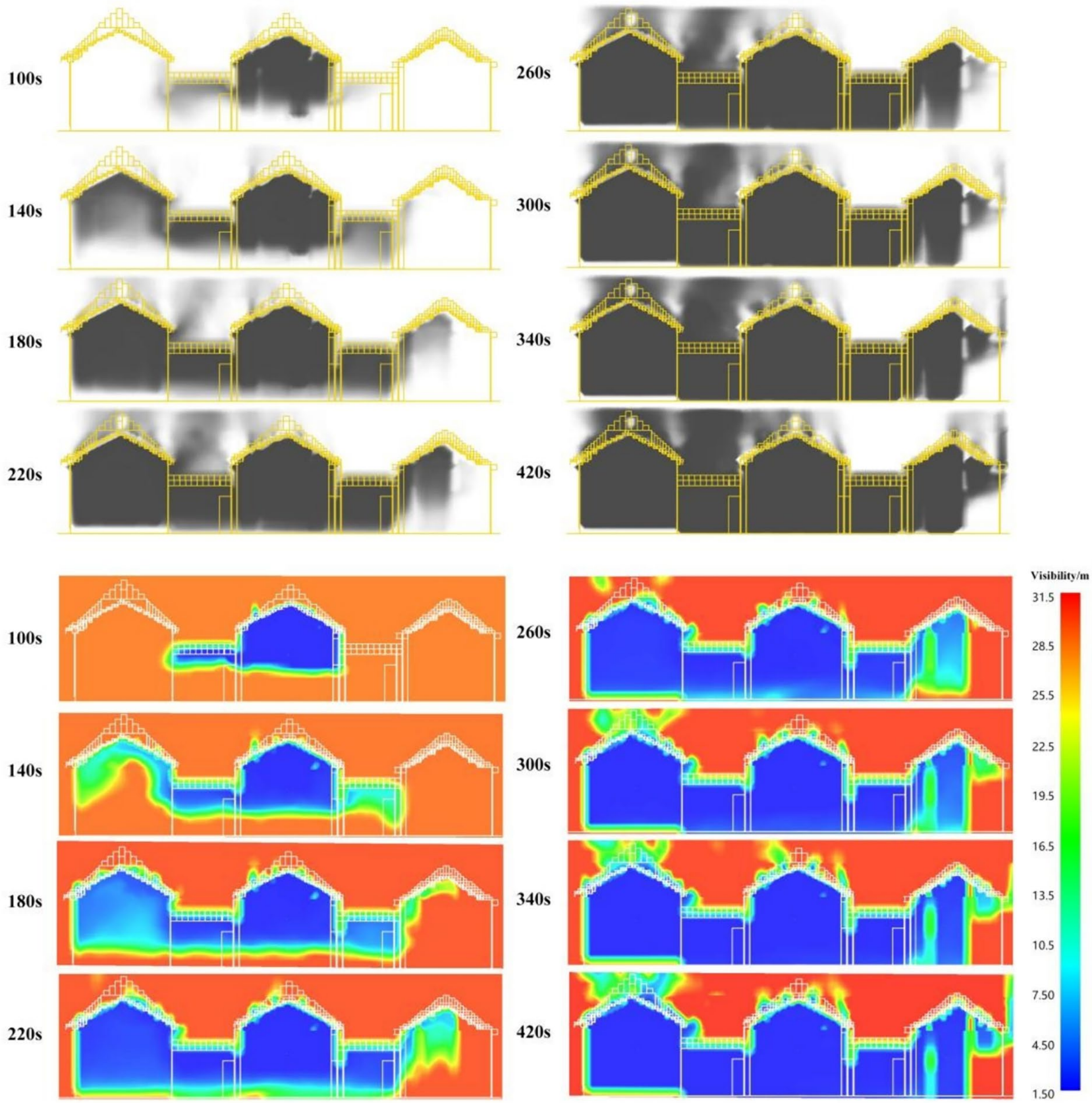


**Fig.13** Smoke flow and smoke visibility under condition two (Source: Own illustration)

shortening the available evacuation time. However, safety evacuation requirements are achievable when the indoor evacuation population is fewer than 50 people.

Therefore, the spatial characteristics of the building's fire scene directly influence fire safety. The available evacuation time is closely related to fire hazard, smoke flow in the fire scene space, and the complexity of indoor space. The required safe egress time is associated with indoor population, evacuation route conditions, and the operation of fire detection and alarm systems.

### Improvement measures

In Guangzhou, glass curtain walls are often used to enclose internal courtyards in ancestral hall buildings, which is a common method for renovation and space utilization. This aims to facilitate the operation of air conditioning systems and the utilization of functional

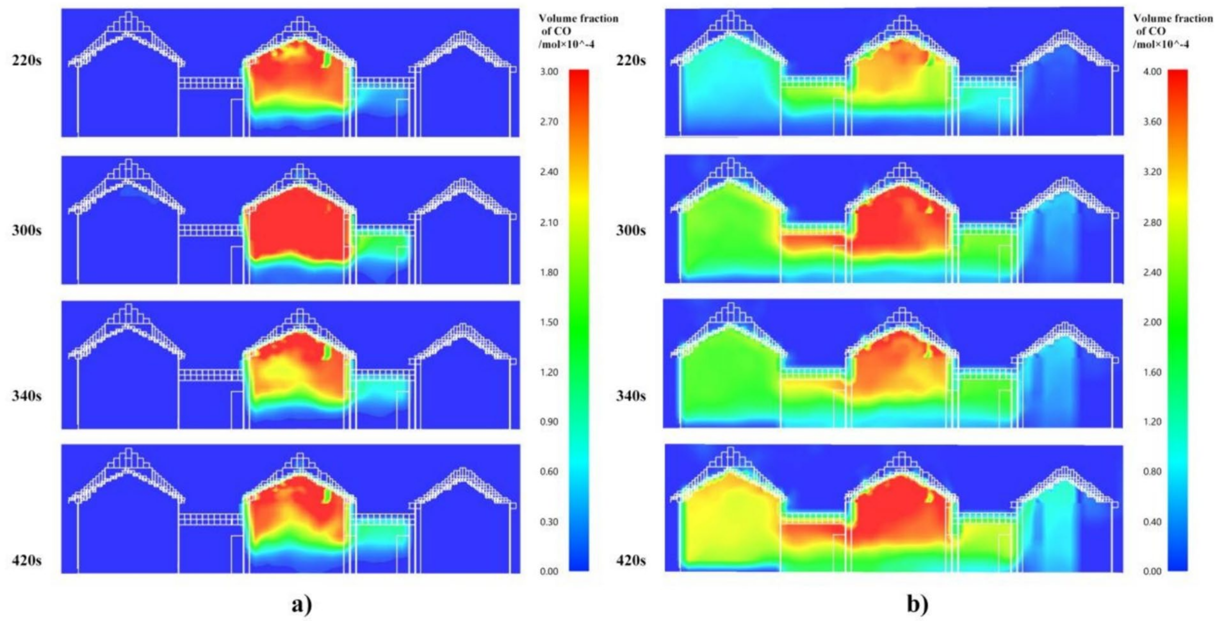


**Fig.14** Volume fraction of CO: **a** Condition one; **b** Condition two (Source: Own illustration)

**Table 4** Available safe evacuation time for fire. (Source: Own calculations)

| Experimental conditions | Time for temperature to reach human tolerance limit (s) | Time for smoke layer to descend to eye-level (s) | Time for severe reduction in smoke visibility impairing evacuation (s) | Time for toxic and harmful gas to reach the human tolerance limit (s) | ASET |
|---|---|---|---|---|---|
| 1 | 220 s | 220 s | 420 s | >420 s | 220 s |
| 2 | 180 s | 180 s | 220 s | >420 s | 180 s |

space. However, this practice severely affects the indoor fire development and safety performance of ancestral hall buildings. Through comparative results from fire numerical simulations and personnel evacuation simulations, we have identified the following non-intrusive improvement measures:

Firstly, controlling the number of indoor occupants is a direct method to effectively reduce the risk during fire evacuations in historic buildings. Many historic buildings open to the public in Guangzhou typically have only one entrance and are 1 to 3 stories high, with complex internal circulation that can easily lead to crowd congestion. Therefore, an intelligent gate management system can be installed at the entrance of historic buildings to effectively control indoor pedestrian flow. When the monitored number of people exceeds the safe range determined by fire simulation and performance evaluation for historic buildings, the entrance gate will automatically close to prevent indoor crowd congestion, thereby reducing the risk during fire evacuations.

Secondly, incorporating ventilation windows or actively linking smoke exhaust facilities with fire alarm equipment as passive smoke exhaust measures in renovation and utilization plans involving glass curtain walls is crucial. Ventilation windows or smoke exhaust facilities should be installed at the junction of the courtyard glass curtain wall and the eaves to promptly discharge smoke from early-stage fires outdoors, drawing the attention of fire alarm personnel. Simultaneously, this can also reduce the accumulation of hot smoke from fires at the base of the historic building's sloped roof, thereby slowing the fire's progression.

## Conclusion

Our study aims to propose a fire design method based on fire load survey data to estimate the fire scale and development process of historic wooden buildings in Guangzhou. Using the representative ancestral hall building Qingyun Academy as a case study, we employ fire dynamics simulation software PyroSim and evacuation

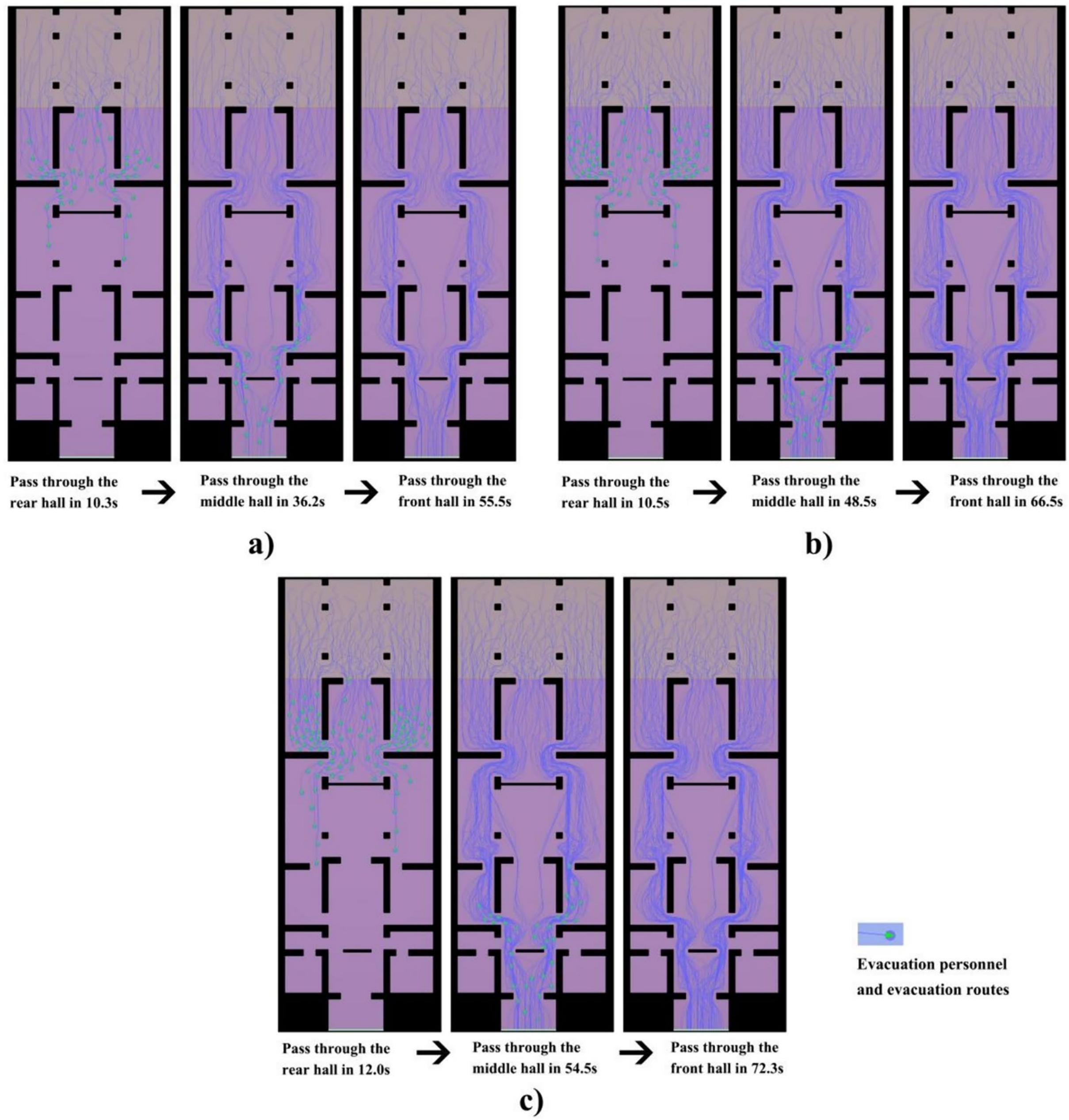


**Fig.15** Evacuation paths and movement times for different numbers of people in condition one: **a** 50 people; **b** 80 people; **c** 100 people (Source: Own illustration)

simulation software Pathfinder to assess and compare the effects of installing enclosed glass curtain walls in internal courtyards on fire safety performance. Additionally, we discuss non-intrusive improvement measures that can be implemented. Below is a summary of our research conclusions:

Fire numerical simulation and evacuation simulation provide effective engineering tools for evaluating the fire safety performance of historic buildings. To enhance the accuracy of fire simulation, we estimated indoor fire development curves based on fire load survey data, combined with the fire load density and combustible material heat release rate specific

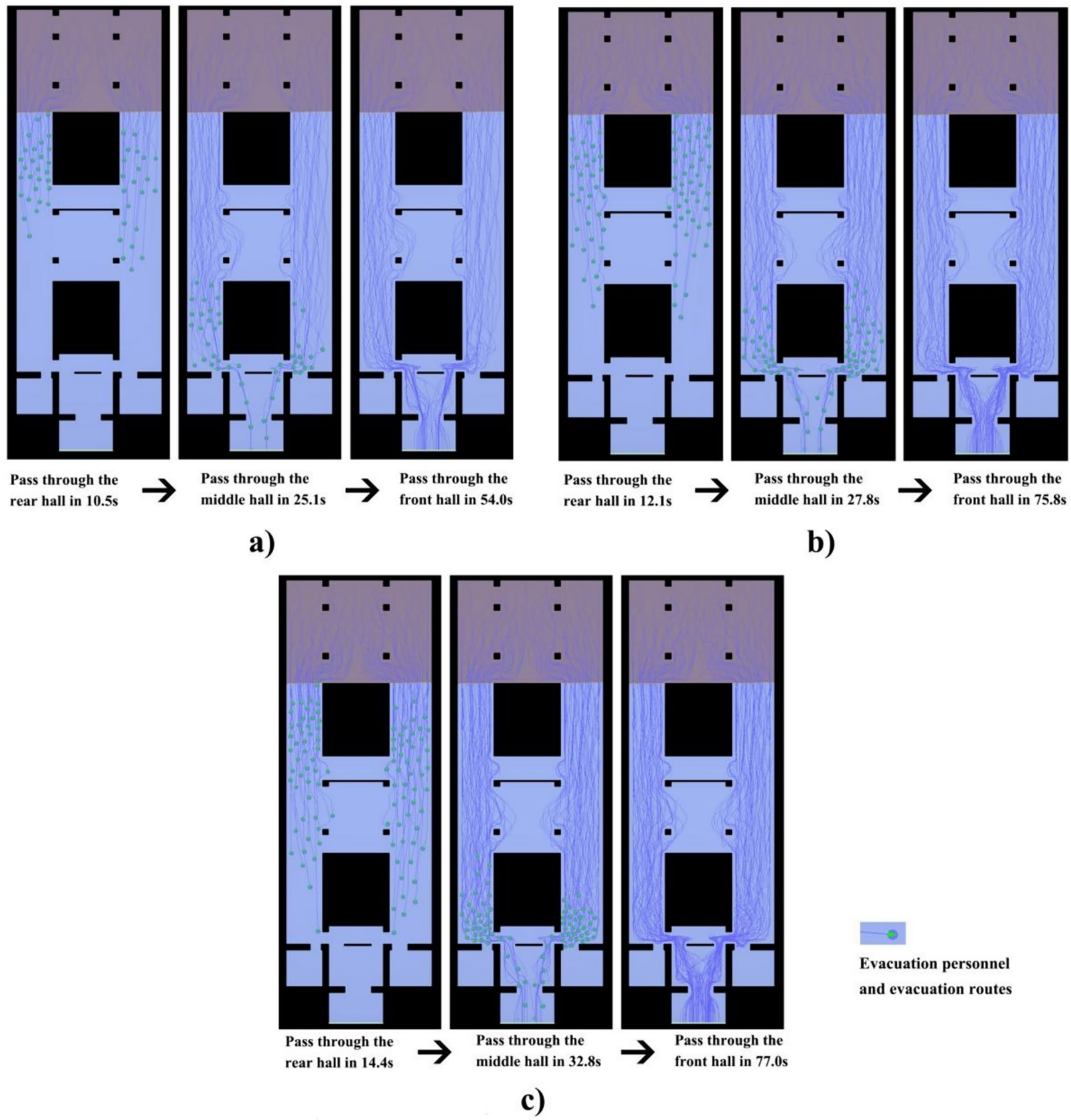


**Fig.16** Evacuation paths and movement times for different numbers of people in condition two: **a** 50 people; **b** 80 people; **c** 100 people (Source: Own illustration)

to ancestral hall buildings. We identified areas with the highest total and density of fire load in ancestral hall buildings as presenting the most adverse fire scenarios.

Installing enclosed glass curtain walls in ancestral hall buildings can extend the path of fire smoke flow and hinder the outward dispersion of high-temperature smoke, thereby accelerating indoor fire development and reducing evacuation time for occupants indoors. Therefore, when retrofitting interior courtyards of ancestral hall buildings with enclosed glass curtain walls, careful attention should be given to the design of ventilation and smoke exhaust facilities. This aids in slowing the spread of fire, providing crucial time for early fire suppression and thereby enhancing fire safety performance.

**Table 5** Evacuation safety assessment (Source: Own calculations)

| Experimental conditions | Evacuated persons | Evacuation time through middle Hall | RSET | ASET | Safe or not? |
|---|---|---|---|---|---|
| 1 | 50 | 154.3 | 183.3 | 220 | Safe |
| | 80 | 172.8 | 199.8 | 220 | Safe |
| | 100 | 181.8 | 208 | 220 | Safe |
| 2 | 50 | 137.7 | 181 | 180 | Safe |
| | 80 | 141.7 | 213.7 | 180 | Unsafe |
| | 100 | 149.2 | 215.5 | 180 | Unsafe |

For Guangzhou's historic wooden structures with single exits, large internal depths, and long evacuation paths, controlling the number of occupants indoors is an effective management measure for reducing the fire hazard in historic buildings. Fire numerical simulation and evacuation simulation methods can determine the maximum indoor occupancy capacity for historic buildings.

This study presents technical methods for evaluating the fire safety performance of renovated and repurposed historic buildings in Guangzhou, contributing to numerical simulation research on fire in unique historic building types within complex environments. Future research should delve deeper, particularly exploring the influence of environmental wind speed on indoor fire development.

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**Author contributions**
XY analyzed the data and wrote the manuscript. XY, SZ and YZ designed and performed the experiments. JZ and YG collected the data and conducted field research for this study. YZ reviewed and revised the manuscript. All authors read and approved the final manuscript.

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**Availability of data and materials**
All data generated during this study are included in this published article.

## Declarations

**Competing interests**
The authors declare no conflict of interests.

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**References**

1. Lisaia D, Zhang C. Morphological and physical characteristics of the historic urban fabric and traditional streets of Xiguan in Guangzhou. J Urban Des. 2022;27(4):441–58.
2. Garcia-Castillo E, Paya-Zaforteza I, Hospitaler A. Fire in heritage and historic buildings, a major challenge for the 21st century. Develop Built Environ. 2023;13: 100102.
3. Li W, Gao X, Du Z, Chen S, Zhao M. The correlation between the architectural and cultural origins of the academies and the ancestral halls in Guangdong, China, from the perspective of kinship politics. J Asian Archit Build Eng. 2023. https://doi.org/10.1080/13467581.2023.2278451.
4. Dingjia Z. Analysis on the Protection and Transformation of the Ancient Buildings of the Le's Ancestral Hall in Huangshi City Fengyangzhuang. 2017 International Conference on Information, Communication and Engineering (ICICE). 2017;pp: 262–265.
5. Torero JL. Fire safety of historical buildings: principles and methodological approach. Int J Archit Herit. 2019;13(7):926–40.
6. Naziris IA, Lagaros ND, Papaioannou K. Optimized fire protection of cultural heritage structures based on the analytic hierarchy process. J Build Eng. 2016;8:292–304.
7. Lei Y, Shen Z, Tian F, Yang X, Wang F, Pan R, et al. Fire risk level prediction of timber heritage buildings based on entropy and XGBoost. J Cult Herit. 2023;63:11–22.
8. Neto JT, Ferreira TM. Assessing and mitigating vulnerability and fire risk in historic centres: a cost-benefit analysis. J Cult Herit. 2020;45:279–90.
9. Guibaud A, Mindeguia JC, Albuerne A, Parent T, Torero J. Notre-Dame de Paris as a validation case to improve fire safety modelling in historic buildings. J Cult Herit. 2024;65:145–54.
10. Sivrikaya F, Küçük Ö. Modeling forest fire risk based on GIS-based analytical hierarchy process and statistical analysis in Mediterranean region. Eco Inform. 2022;68: 101537.
11. Hu J, Xie X, Shu X, Shen S, Ni X, Zhang L. Fire risk assessments of informal settlements based on fire risk index and Bayesian network. Int J Environ Res Public Health. 2022;19(23):15689.
12. Falk MT, Hagsten E. Assessing different measures of fire risk for Cultural World Heritage Sites. Herit Sci. 2023;11(1):189.
13. Durak S, Erbil Y, Akıncıtürk N. Sustainability of an architectural heritage site in Turkey: fire risk assessment in Misi village. Int J Archit Herit. 2011;5(3):334–48.
14. Yang L, Liu W, Liu Q, Liu S, Tong Y, Xiao Z, et al. Full-scale fire experiment of timber buildings in rural areas of Southwest China. Int J Archit Herit. 2023;17(9):1505–24.
15. Lassus J, Courty L, Garo JP, Studer E, Jourda P, Aine P. Estimation of species concentrations during a fire in a reduced-scale room. J Fire Sci. 2016;34(1):30–50.
16. Weinschenk CG, Overholt KJ, Madrzykowski D. Simulation of an attic fire in a wood frame residential structure, Chicago IL. Fire Technol. 2016;52:1629–58.
17. Petrini F, Aguinagalde A, Bontempi F. Structural fire risk for heritage buildings by the performance-based engineering format. Int J Archit Herit. 2023;17(7):1171–94.
18. Granda S, Ferreira TM. Large-scale vulnerability and fire risk assessment of the historic centre of Quito Ecuador. Int J Archit Herit. 2021;15(7):1043–57.
19. Granda S, Ferreira TM. Assessing vulnerability and fire risk in old urban areas: application to the historical centre of Guimarães. Fire Technol. 2019;55:105–27.
20. Ferreira TM, Vicente R, da Silva JARM, Varum H, Costa A, Maio R. Urban fire risk: evaluation and emergency planning. J Cult Herit. 2016;20:739–45.
21. Giraldo M, Rodríguez-Trujillo V, Burgos C. Numerical-simulation research on fire behavior of a historic industrial building. In 8th international conference on structural analysis of historical constructions proceedings, Wrocław Poland. 2012;1–3 pp: 525–533.
22. Long X, Zhang X, Lou B. Numerical simulation of dormitory building fire and personnel escape based on Pyrosim and Pathfinder. J Chin Inst Eng. 2017;40(3):257–66.
23. Li X, Qin R. Performance-based firefighting in dense historic settlements: an exploration of a firefighting approach combining value and risk assessment with numerical simulation. Front Archit Res. 2022;11(6):1134–50.

24. Tung SF, Su HC, Tzeng CT, Lai CM. Experimental and numerical investigation of a room fire in a wooden-frame historical building. Int J Archit Herit. 2018;14(1):106–18.
25. Jian W, Jinsong H, Kumar K, Kumar S. Modeling and validation of fire induced airflow in a room. Int Symp Saf Sci Technol. 2004;4:1164–70.
26. Huang X, Li H, Li X, Zhang L. Fire numerical simulation analysis for large-scale public building in 3D GIS. IGARSS 2019–2019 IEEE International Geoscience and Remote Sensing Symposium. 2019;7522–25.
27. Roh JS, Yang SS, Ryou HS, Yoon M, Jeong YT. An experimental study on the effect of ventilation velocity on burning rate in tunnel fires—heptane pool fire case. Build Environ. 2008;43(7):1225–31.
28. Shen TS, Huang YH, Chien SW. Using fire dynamic simulation (FDS) to reconstruct an arson fire scene. Build Environ. 2008;43(6):1036–45.
29. Zhang XG, Guo YC, Chan CK, Lin WY. Numerical simulations on fire spread and smoke movement in an underground car park. Build Environ. 2007;42(10):3466–75.
30. Zhang F, Shi L, Liu S, Shi J, Shi C, Xiang T. CFD-Based Fire risk assessment and control at the historic Dong wind and rain bridges in the western hunan region: the case of huilong bridge. Sustainability. 2022;14(19):12271.
31. Watts JM, Solomon RE. Fire safety code for historic structures. Fire Technol. 2002;38:301–10.
32. Bukowski RW, Nuzzolese V. Performance-based fire protection of historical structures. Fire Technol. 2009;45:23–42.
33. Claret AM, Andrade AT. Fire load survey of historic buildings: a case study. J Fire Prot Eng. 2007;17(2):103–12.
34. Li J, Li H, Zhou B, Wang X, Zhang H. Investigation and statistical analysis of fire loads of 83 historic buildings in Beijing. Int J Archit Herit. 2018. https://doi.org/10.1080/15583058.2018.1550535.
35. Chow WK. Fuel load and peak heat release rate correlations in post-flashover room fires. Heat Transfer Eng. 2010;31(3):250–4.
36. Bryant RA, Ohlemiller TJ, Johnsson EL, Hamins A, Grove BS, et al. The NIST 3 megawatt quantitative heat release rate facility-description and procedures. US Department of Commerce, National Institute of Standards and Technology. 2004.
37. Chen Y, Sharudin SA, Chen R. Study on the evolution of plane shape of Guangfu Ancestral hall buildings and the construction of type genealogy in the ming and qing dynasties. J Archit Res Devel. 2024;8(1):1–7.
38. Su HC, Tung SF, Tzeng CT, Lai CM. Survey and experimental investigation of movable fire loads in Japanese-style wooden historical buildings. Int J Archit Herit. 2019. https://doi.org/10.1080/15583058.2019.1587040.
39. Chow WK, Ngan SY, Lui GCH. Movable fire load survey for old residential highrise buildings in Hong Kong. WIT transactions on The built environment. 2007; 94.
40. Džolev I, Laban M, Draganić S. Survey based fire load assessment and impact analysis of fire load increment on fire development in contemporary dwellings. Saf Sci. 2021;135: 105094.
41. Xie Q, Xiao J, Gardoni P, Hu K. Probabilistic analysis of building fire severity based on fire load density models. Fire Technol. 2019;55:1349–75.
42. Barnett A, Cheng C, Horasan M, He Y, Park L. Fire load density distribution in school buildings and statistical modelling. Fire Technol. 2022. https://doi.org/10.1007/s10694-021-01150-w.
43. Liao L, Li H, Li P, Bao X, Hong C, Wang D, et al. Underground evacuation and smoke flow simulation in Guangzhou international financial city during fire. Fire. 2023;6(7):266.
44. Caliendo C, Ciambelli P, Del Regno R, Meo MG, Russo P. Modelling and numerical simulation of pedestrian flow evacuation from a multi-storey historical building in the event of fire applying safety engineering tools. J Cult Herit. 2020;41:188–99.
45. Bernardini G, Azzolini M, D'Orazio M, Quagliarini E. Intelligent evacuation guidance systems for improving fire safety of Italian-style historical theatres without altering their architectural characteristics. J Cult Herit. 2016;22:1006–18.
46. Ronchi E, Corbetta A, Galea ER, Kinateder M, Kuligowski E, McGrath D, et al. New approaches to evacuation modelling for fire safety engineering applications. Fire Saf J. 2019;106:197–209.
47. Ronchi E. Developing and validating evacuation models for fire safety engineering. Fire Saf J. 2021;120: 103020.
48. Lu L, Chan CY, Wang J, Wang W. A study of pedestrian group behaviors in crowd evacuation based on an extended floor field cellular automaton model. Transp Res Part C Emerg Technol. 2017;81:317–29.
49. Hu LH, Huo R, Wang HB, Li YZ, Yang RX. Experimental studies on fire-induced buoyant smoke temperature distribution along tunnel ceiling. Build Environ. 2007;42(11):3905–15.
50. Węgrzyński W, Krajewski G, Kimbar G. Smart smoke control as an efficient solution for smoke ventilation in converted cellars of historic buildings. Fire Technol. 2021;57:3101–23.
51. Liu Y, Wu W. Analysis on smoke visibility in fire environment from the perspectives of path curvature and view direction. Int J Heat Technol. 2019. https://doi.org/10.18280/ijht.370423.
52. Park H, Meacham BJ, Dembsey NA, Goulthorpe M. Conceptual model development for holistic building fire safety performance analysis. Fire Technol. 2015;51:173–93.


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