Discussion on the Analysis of Fire Hazard in the Central Hall of a Historical Building

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Abstract. This study focuses on the inadequate compliance of natural smoke exhaust windows in the central hall of a historical building in Shanghai. Taking into consideration the preservation of the authenticity of the historical structure, five fire scenarios were established to evaluate the fire hazard in the central hall based on different fire heat release rates, fire growth coefficients, number of open windows and window response times. Considering the actual conditions of the historical building and its function as a medical facility, the study also analyzed the rationality of setting fire scenario parameters for evacuation time and fire safety assessment. The research findings indicate that the upper smoke temperature is significantly influenced by the values of heat release rate and the number of open windows. Increasing the number of open windows by 60% can extend the time for the upper smoke temperature to reach a dangerous state by approximately 10%.

Keywords: historical building; evacuation time; fire scenarios; fire heat release rate; hazard assessment.

1. Introduction

Historical buildings are the cultural memory and precious resources of a city. Many historical buildings face challenges in meeting fire safety regulations while preserving their authenticity. Balancing the preservation of historical buildings' authenticity, functionality and ensuring fire safety for occupants has become an important topic in current research on fire protection for historical buildings.

The South Building of a hospital in Shanghai was constructed in 1926. It is one of the first batch of outstanding historical buildings and cultural heritage protection units in Shanghai. In order to meet the new healthcare demands, the hospital initiated an upgrade and renovation project for the South Building in 2020. In the fire protection design of the South Building, the existing natural smoke exhaust windows in the central hall do not meet the current regulatory requirements. The central hall currently has five suspended high windows with an area of 1.9 m^2 each. According to the current regulations, if only natural smoke exhaust is used, the central hall should have natural smoke exhaust windows with an area of at least 28 m^2, and manual opening mechanisms for smoke exhaust windows should be installed at a height of 1.3-1.5 m above the floor.

Considering the historical appearance of the building, the hospital and design units decided to use only natural smoke exhaust in the central hall. The five high windows would be transformed into electric smoke exhaust windows with the addition of remote manual opening devices. However, the smoke exhaust performance of the windows needs to be simulated in a fire scenario to demonstrate their fire safety.

2. Research Methods

2.1 Required safe egress time

The evaluation of the fire safety of the natural smoke exhaust windows in the central hall is based on whether occupants can safely evacuate after a fire. When the Required Safe Egress Time (RSET) is less than the Available Safe Egress Time (ASET), it is determined that the natural smoke exhaust windows in the central hall can meet the requirements for safe evacuation of occupants [1,2].

$$RSET = T_d + T_b + T_c + T_s \qquad (1)$$

T_d - the time required for the fire alarm system to sound the alarm after a fire occurs. The central hall uses a centralized alarm system and T_d is set to 20 seconds.

T_b - the response time of occupants after hearing the fire alarm. The central hall is equipped with fire broadcasting and fire alarm devices with voice synchronizers and T_b is set to 10 seconds.

T_c - the preparation time before occupants start evacuating. Considering the actual situation, T_c is set to 80 seconds.

T_s - the time required for occupants to evacuate to a safe area. The maximum evacuation distance is set as S = 52m. Due to the specific nature of this hospital, the evacuation of occupants can proceed smoothly after a fire and congestion at fire doors is not considered [3]. The evacuation speed is set as V=1m/s. T_s = S/V = 52s.

$$RSET = T_d + T_b + T_c + T_s = 20 + 10 + 80 + 52 = 162s$$

2.2 FDS model

In this study, PyroSim software was used to create an FDS model and five different fire scenarios were simulated and analyzed to determine the value of ASET. As shown in Figure 1, the FDS model of the central hall has dimensions of 19.05m (length) × 14.36m (width) × 7.67m (height). The second-floor corridor is located at an elevation of 4.01m, with a clear width of 2.5m. There are five square window openings measuring 1.38m × 1.38m above the exterior wall of the hall. The FDS model is divided into a grid of 52 (length) × 40 (width) × 20 (height), resulting in a total of 41,600 cells. The size of each grid unit is 0.37m (length) × 0.36m (width) × 0.38m (height). The doors in the hall are not involved in the smoke exhaust calculation and are set to a closed state. The height of the main beam in the hall is 1.05m, which has a certain slowing effect on the horizontal spread of smoke [4,5].

Fig.1 Central hall FDS model

2.3 Setting Fire Scenarios

Based on different maximum fire heat release rates, fire growth factors, the number of open windows and the window response time, five different scenarios were established to analyze the fire hazard in the central hall (Table 1). In this study, the maximum fire heat release rate (HRR) was set to 4MW [6].

Table 1. Parameters of five fire scenarios

① The fire reaches a steady state with a maximum fire heat release rate (HRR) of 2MW immediately after ignition. After 30 seconds, 5 windows are opened for smoke exhaust.	② The fire is set to a medium growth rate with a fire growth factor of 0.011 kW/s². The fire reaches a steady state after 292 seconds with a maximum HRR of 1MW. After 15 seconds,3 windows are opened for smoke exhaust.	③ The fire is set to a fast growth rate with a fire growth factor of 0.044 kW/s². The fire reaches a steady state after 292 seconds with a maximum HRR of 4MW. After 30 seconds,5 windows are opened for smoke exhaust.
④ The fire is set to a fast growth rate with a fire growth factor of	⑤ The fire is set to a fast growth rate with a fire growth factor of 0.044	

| 0.044 kW/s². The fire reaches a steady state after 292 seconds with a maximum HRR of 4 MW. After 15 seconds,5 windows are opened for smoke exhaust.	kW/s². The fire reaches a steady state after 292 seconds with a maximum HRR of 4 MW. After 15 seconds,3 windows are opened for smoke exhaust.	

2.4 Fire Hazard Assessment

In this study, the evaluation area is the second-floor corridor and the parameters for fire hazard assessment include:①T_1-Time required for the smoke temperature at a height of 1.5m above the second-floor corridor floor to reach 60°C;②T_2-Time required for the smoke temperature at a height of 2.1m above the second-floor corridor floor to reach 180°C ;③T_3-Time required for the visibility at a height of 1.2m above the second-floor corridor floor to drop below 5m ;④T_4-Time required for the CO volume fraction at a height of 1.2m above the second-floor corridor floor to reach 0.25%[7,8].

3. Simulation results

3.1 Scenario 1

Scenario 1 is considered as the reference case, where no fire growth time is specified, and the heat release rate (HRR) is set to 2MW. After 30 seconds, 5 windows are opened for natural smoke ventilation. The fire simulation results indicate that the smoke temperature and visibility at the human eye's characteristic height reach a hazardous state and this condition persists for a short duration (Table 2).
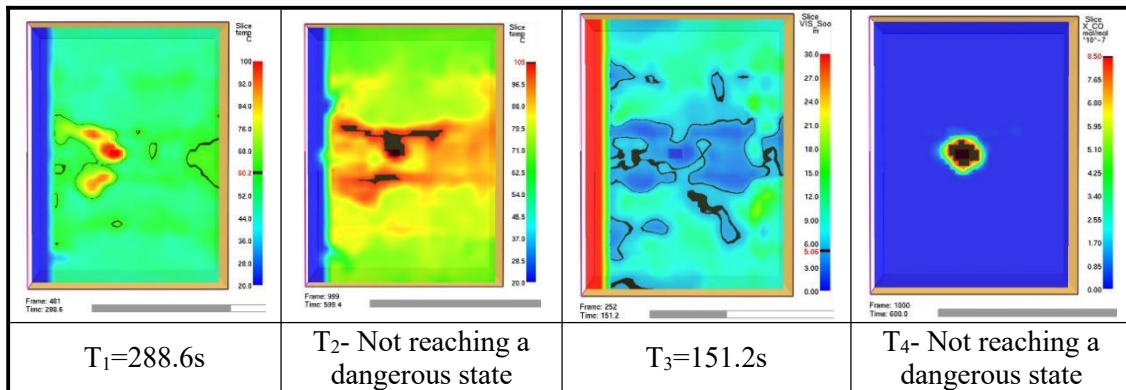
Table 2. Smoke distribution and hazardous times in Scenario 1

T_1=35.4s	T_2- Not reaching a dangerous state	T_3=10.8s	T_4- Not reaching a dangerous state
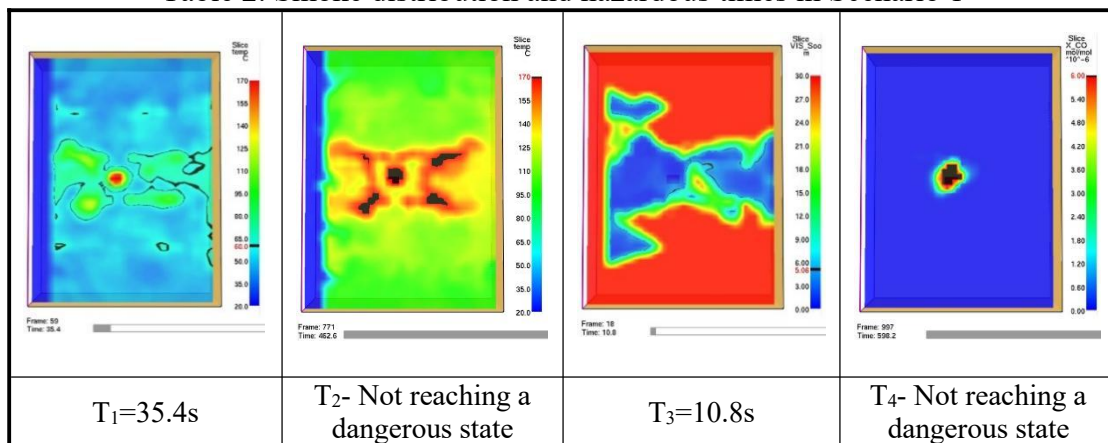
3.2 Scenario 2

Scenario 2 is also considered as a comparative scenario, taking into account the possibility of using portable fire extinguishing equipment during firefighting. The fire development in this scenario is slower, with an HRR of 1MW. After a short period of time, 3 windows are opened for natural smoke ventilation. The fire simulation shows that the smoke temperature and visibility at the human eye level also reach hazardous conditions, but for a longer duration (Table 3).

Table 3. Smoke distribution and hazardous times in Scenario 2

| $T_1=288.6s$ | T_2- Not reaching a dangerous state | $T_3=151.2s$ | T_4- Not reaching a dangerous state |

3.3 Scenario 3

Scenario 3 is designed to resemble real-life conditions more closely. The fire development in this scenario is faster with an HRR of 4MW. After 30 seconds, 5 windows are opened for natural smoke ventilation. The fire simulation shows that the smoke temperature at the human eye level, upper smoke temperature, and visibility all reach hazardous conditions (Table 4).

Table 4. Smoke distribution and hazardous times in Scenario 3

| $T_1=171.0s$ | $T_2=309.6s$ | $T_3=81.6s$ | T_4- Not reaching a dangerous state |
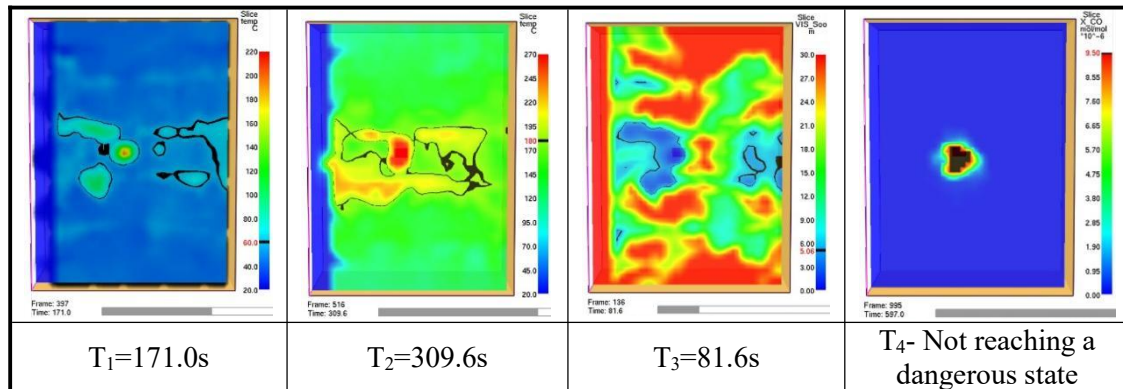
3.4 Scenario 4

Scenario 4 involves rapid fire development with an HRR of 4MW. After a short period of time, 5 windows are opened for natural smoke ventilation. The fire simulation indicates that the smoke temperature at the human eye level, upper smoke temperature and visibility all reach hazardous conditions (Table 5).

Table 5. Smoke distribution and hazardous times in Scenario 4

| $T_1=173.4s$ | $T_2=306.6s$ | $T_3=80.5s$ | T_4- Not reaching a dangerous state |
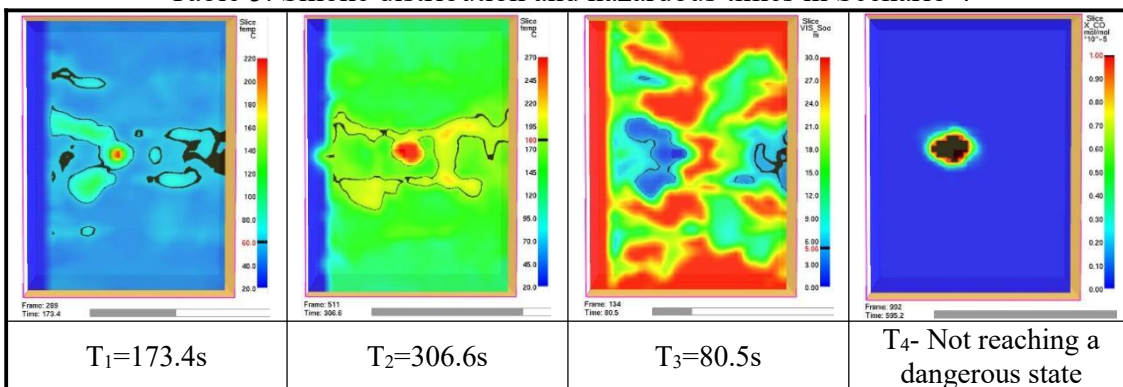
3.5 Scenario 5

Scenario 5 involves rapid fire development with an HRR of 4MW. After a short period of time, 3 windows are opened for natural smoke ventilation. The fire simulation indicates that the smoke

temperature at the human eye level, upper smoke temperature and visibility all reach hazardous conditions (Table 6).

Table 6. Smoke distribution and hazardous times in Scenario 5

T_1=169.8s	T_2=280.2s	T_3=79.2s	T_4 -Not reaching a dangerous state
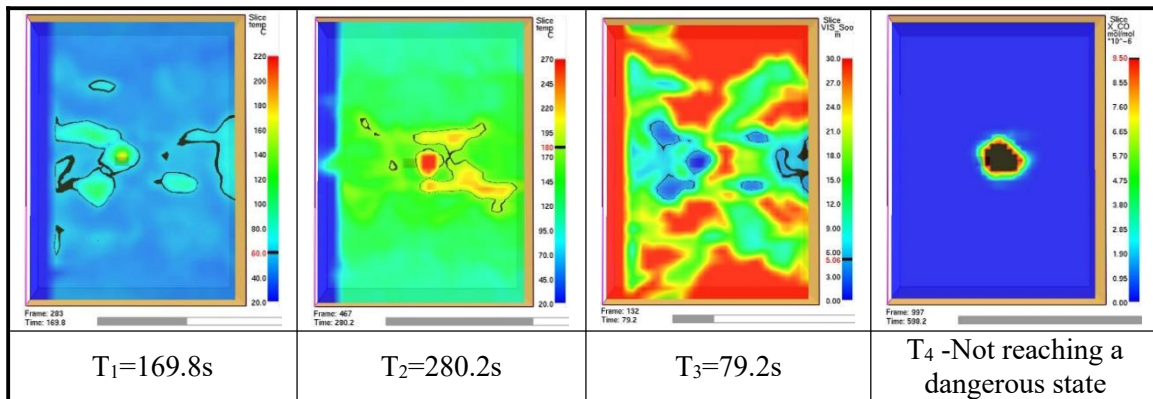
4. Data Analysis

The hazardous times for Scenario 1-5 is listed in Table 7.

Table 7. Hazardous times of five fire scenarios

	T_1	T_2	T_3	T_4
Scenario 1	35.4s	—	10.8s	—
Scenario 2	288.6s	—	151.2s	—
Scenario 3	171.0s	309.6s	81.6	—
Scenario 4	173.4s	306.6s	80.5s	—
Scenario 5	169.8s	280.2s	79.2s	—

The fire simulations indicate that the CO concentrations in all scenarios do not reach hazardous levels. However, the smoke temperature and visibility at the human eye level reach dangerous conditions. The upper smoke temperature is more influenced by the HRR value, as it do not reach hazardous levels when HRR is below 4MW. Comparing Scenario 4 and Scenario 5, it can be observed that increasing the number of open windows by 60% can extend the time for the upper smoke temperature to reach hazardous levels by approximately 10%.

Scenario 1 represents an extreme case with no fire development time, resulting in very short T_1 and T_3 values, indicating high danger. It is used as a comparative scenario in this study. Scenario 2 considers the involvement of firefighting equipment, resulting in relatively longer T_1 and T_3 values. This suggests that early intervention of firefighting equipment during a fire can effectively increase the available safe evacuation time and reduce fire hazards. The differences in T_1 and T_3 values between Scenario 3, Scenario 4 and Scenario 5 are not significant. Despite having fewer open windows, Scenario 5 has relatively higher fire hazards and the impact of window opening response time on fire hazards is not significant.

From Table 7, it can be observed that the T_1 values for Scenario 3, Scenario 4 and Scenario 5 are all greater than the required safe egress time (RSET) of 162s, while the T_3 values are all lower than RSET. This indicates the significant impact of visibility on safe evacuation during a fire. Considering that the central hall is located in the middle of the evacuation path, with fire doors on both sides acting as barriers to smoke entering the ward area and the low occupancy rate of the hospital wards, as well as the simplicity of the evacuation path, this study suggests that using the time for the smoke temperature to reach 60°C at the human eye level (T_1) as the available safe egress time (ASET) is reasonable. In conclusion, the automatic opening of the natural smoke vents can effectively control smoke in the central hall during a fire and meet the requirements for safe evacuation[9].

5. Summary

In the current preservation of historical buildings, various fire safety issues need to be considered while protecting their authenticity. It is important to take into account the actual conditions of historical buildings and establish reasonable fire scenarios for fire simulation and risk assessment. This study has made preliminary explorations into the methods and rationality of fire risk assessment for historical buildings. Fire protection for historical buildings is a comprehensive engineering project that requires the collaboration of stakeholders. Only by establishing fire evaluations based on extensive data research and analysis can we provide scientifically reliable design and assessment methods for fire protection in historical buildings.

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