Hydraulic and Civil Engineering Technology VII
M. Yang et al. (Eds.)

doi:10.3233/ATDE220871

Fire Safety Design Strategy of Special Space at the Top of Super High-Rise Building

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Abstract. A large number of super high-rise buildings have been built in many cities in China, which not only improve the urban land utilization, but also enhance the local reputation of cities. However, super high-rise buildings bring about many firefighting problems in the meantime, such as the accessibility of firefighters, safe egress, occupant staging and evacuation, stack effect in high-rise buildings, the increase of fire load, and the mixing of different types of occupants. Especially, the top portion of the super high-rise building can increase commercial property value for the developer because of its good landscape and attraction of business facilities such as sightseeing, dining, and meeting, but these activities might increase the difficulty of firefighting and rescue. In this paper, taking a super high-rise building close to 500 m as an example, the fire safety challenges of long evacuation time and long evacuation distance in the building were analyzed, and a comprehensive life safety analysis with fire simulation of the topping crown of the building for sightseeing and dining was carried out. The proposed life and fire safety strategy can meet both the fire safety design intend of the China fire codes and the basic requirements of safe egress in fire. The design method in this paper can be used as a credible reference to guide the design of special space at the top of similar super high-rise buildings in the future.

Keywords. Super high-rise building, observation deck, fire safety design, simulation analysis, evacuation

1. Introduction

In order to alleviate the increasing shortage of urban land, super high-rise buildings have sprung up in large and medium-sized cities. Super-high-rise buildings not only improve the urban land utilization, but also enhance the local reputation of cities, such as Empire State Building in New York, Tokyo TV Tower, Shanghai Tower, Burj Khalifa in Dubai, etc. As of 2018, China had built 686 super high-rise buildings over 200 m [1]; Among the 50 tallest buildings in the world, China occupies for 44% up to 22 buildings. If the statistical scope is extended to the buildings under construction, there are 47 additional buildings with a height of more than 300 m in China that will be

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completed soon. There is no doubt that the development of super high-rise buildings in China have entered a peak period [2].

Although these skyscrapers alleviate the shortage of urban land, they pose great challenges to public safety. For example, on April 22nd, 2014, the facade of a 34-story residential building near Xinghai Square in Dalian, Liaoning Province caught a fire, and the fire developed rapidly that the smoke spread to the top floor. Fortunately, the fire happened on working hours, and most residents had gone to work, so the fire caused no casualties. On February 3rd, 2011, the Wanxin International Building of Shenyang Dynasty caught fire. The 152m-high apartment building was basically completely burned down and the fire spread to another high-rise tower. On November 15th, 2010, a 28-storey apartment in Jingan District, Shanghai caught fire. 58 people died and more than 70 people injured in the fire, which caused an economic loss of nearly RMB500 million. On December 12th, 2007, a big fire broke out in Wenfu Mansion, Wenzhou, Zhejiang Province, causing 21 deaths and 2 serious injuries. According to the firefighting rescue capabilities of large and medium-sized cities, the firefighting on floors above 100 m mainly depends on the automatic fire extinguishing facilities inside the building and the on-site firefighting by firefighters. Therefore, in order to avoid the tragedy of mass casualties caused by fire, it is particularly important to safely evacuate people in the building while strictly eliminating fire hazards. Especially, many super high-rise buildings have housed special functional places such as sightseeing, dining, etc. at the top because of their good view, which will bring uncertain impact on the occupant evacuation. All sectors of society, including fire approval departments, design institutes, fire consultants and fire products R&D institutions, have continuously explored and studied the evacuation safety of super high-rise buildings.

Taking a super high-rise building close to 500m as an example, this paper analyzes the difficulties of long evacuation time and long evacuation distance in the building, and a comprehensive life safety analysis with fire simulation analysis at the top of the building for sightseeing and dining was carried out, so as to verify whether the proposed fire safety design strategy can meet both the basic requirements of safe egress in addition to the fire code fire safety intend. This design method can also be referred to as a credible reference to guide the design of special functional space of the top area of similar super high-rise buildings in the future.

2. Challenge of Fire Safety in Super High-rise Buildings

The fire safety of high-rise buildings has always been concerned by the public and the fire department, and the fire department in the United States has also compiled a specified report on the fire rescue of high-rise buildings [3]. The fire safety problems related to high-rise buildings can be summarized into the following six main fields: firefighting accessibility of firefighters, safety exits and human evacuation, natural forces such as stack effect, the increase of fire loading, the mixing of different kinds of occupant and the threat of vertical shafts in buildings. Among the above fire safety challenges, half of them is related to the evacuation of people in buildings (overlong evacuation distance, high density of people and different kinds of people), so the evacuation strategy of people in high-rise buildings will be the area of focus.

Due to the great height of high-rise buildings, it can be predicted that it will take longer time for people to reach the ground floor. During human evacuation phase, people usually need to arrive at the entrance door of the stairs from their original compartment and then evacuate up to 600 meters in the vertical direction in the super high-rise building by thousands of steps in the stairwell in order to reach the ground. Regardless of the decrease of evacuation speed caused by fatigue, many people will queue up at the entrance of each stair, which will dramatically increase the evacuation time. Some local codes require the provision of additional facilities, such as refuge floors, to ease the evacuation congestion in super high-rise buildings.

It is more complicated that the number of people vertically stacked in super high-rise buildings. Compared with low-rise buildings, the floor area of buildings or the utilization rate of stairs per meter, high-rise buildings are obviously far larger. In addition, modern super high-rise buildings are often designed as multi-occupancy comprehensive buildings, usually including sightseeing and dining facilities in the top area, hotels and service apartments on the high place, and business or conference facilities in office areas and podium buildings on the lower floors. Different kinds of people are with different familiarity with the buildings, and the differences among evacuees will make the evacuation behavior further unpredictable.

The special functional space in the top area is the key and the main challenge in the fire protection design of super high-rise buildings. Because of the height of the super high-rise building, its top area has a good view that can attract business activity, which can create greater commercial value for the building, especially sightseeing, dining, meeting and other facilities. The space is generally open to the public, and the target people are people who don't visit the building frequently, like children and the elderly who are unfamiliar with the building. This space is located at the top of the tower, which will greatly increase the difficulty in evacuation. In addition to the fire protection design based on the fire code requirements, fire engineering method should also be adopted to demonstrate and analyze the actual safety level, so as to ensure the safety egress of occupants in fire condition in special spaces in the top area of super high-rise buildings.

3. Fire Engineering Analysis

Fire engineering analysis is the elementary tool for comprehensive fire safety analysis. The method is to use the principle of fire protection engineering to analyze and demonstrate the most primitive fire protection foundation, and realize the fire protection and life safety goals, such as fire development and spread, smoke flow, occupant tolerance analysis, fire detection and control, evacuation design, personnel psychology, structural fire resistance, fire risk, fire protection management and a series of issues related to fire safety, which need to be considered comprehensively. This is an interdisciplinary subject, and it is also very suitable for the fire safety analysis of super high-rise buildings, since the design requirements are not completely covered by the current fire code. Based on the comprehensive fire and evaluation analysis tool adopted as shown in figure 1, it can bring innovative fire safety design to buildings, and is beneficial to the fire safety design of super high-rise buildings including:

Flexible design: the characteristics of architectural design, such as building height, different functions and huge volume, which are not completely covered by traditional fire protection design. Making use of the performance design of fire protection engineering, we can reasonably demonstrate the safety and related risks of the design and put forward specific protection measures to make the design feasible.

Higher safety level: fire analysis and evaluation are based on the principles of fire engineering, and basic principles of safety, such as fire load analysis, fire scenario and fire risk, combined with the latest research results and technologies. Fire protection analysis and evaluation also take into account the fire safety level requirements stipulated in the code and the lessons learned from previous fire cases. This analysis method can provide a fire safety level equal to or higher than the requirements of the current code.

Cost-effective scheme: the fire engineering design will consider the required fire protection system according to the fire scenarios to meet the performance requirements of fire safety. This method can optimize the setting of fire protection system and avoid waste. At the same time, it will supplement the fire-fighting facilities that need to be strengthened to ensure the maximum cost-effectiveness of the invested facilities and optimize the future operation and maintenance costs.

Quantified risk level: Fire engineering design will evaluate fire load, fire development, smoke spread, personnel tolerance in fire, etc. The evaluation conclusion includes the quantitative risk level of personnel and firefighting rescue in the project. Fire protection analysis will ensure that the fire risk of engineering design is under control within an acceptable level.

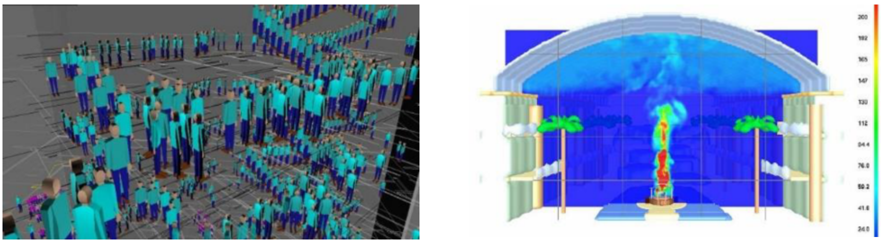

Figure 1. Computational simulation tools used in fire engineering analysis.

4. Project Case

As a case study, a super high-rise building with a height of almost 500 meters in the center of China has been studied. The main function of the tower is office, and there are several floors of special functional places in the building crown with a total height of about 70 meters at the top portion of the tower, including sightseeing, dining, art exhibition and other functions. One of the sightseeing spaces with a height of 55 meters is the important feature of the project as shown in figure 2. There are circular trails and connecting steps in the space. While enjoying the scenery outside, you can feel the crisscross atmosphere in the building. In addition, outdoor sightseeing platforms are also provided on roofs with different elevations. The whole featured functional place covers an area of over 10,000 square meters, with a maximum capacity of about 3,000 people.

Figure 2. Special sightseeing space renderings of the tower and the top area.

The fire protection design scheme of the project is basically implemented according to the national fire code [4]. In addition to referring to the national design of strengthening measures for buildings over 250 m [5], the fire protection design of the characteristic space at the top of the tower is strengthened by increasing the evacuation stairs of sightseeing stairs to reach the refuge floor, adding auxiliary evacuation elevators, setting independent evacuation stairs through the sightseeing space, increasing the smoke exhaust rate of large space, and increasing the area of refuge areas, etc.

In order to verify the effectiveness of the proposed fire control measures, the analysis method of fire safety engineering has been adopted in the project: analyse and simulate the situation of different fire scenarios using the computer model of fire dynamics and smoke flow, determine the required smoke extraction method and rate, analyse and simulate the occupant evacuation with the computer model, and finally verified the fire control facilities and strategies according to the analysis and simulation results.

5. Analysis and Simulation of Fire Protection

The goal of the fire protection design scheme is to make the fire protection design meet the characteristics of the building and the requirements of use. According to the characteristics of the project case, the objectives of the fire safety strategy of the project are determined as follows:

Human safety evacuation: when a fire breaks out in the special space of the top area, all occupant in the special space of the top area can evacuated to the final safe place during available safety evacuation time.

Fire spread limitation in the building: when a fire breaks out in a special space in the roof area, the fire extinguishing system can effectively control the spread of the fire, and the smoke exhaust system can effectively remove smoke and heat, so that the fire can be controlled in the set fire zone.

Protecting life safety is the main purpose of performance-based design of fire protection, and the safe evacuation of people in buildings after a fire is the direct embodiment of this purpose. Generally speaking, the safety of personnel evacuation depends on the time required for the fire to develop into a danger threated to people and the time required for personnel to evacuate to a safe place. As shown in figure 3, the standard of personnel life safety is: the available safe evacuation time ASET > the required safe evacuation time RSET.

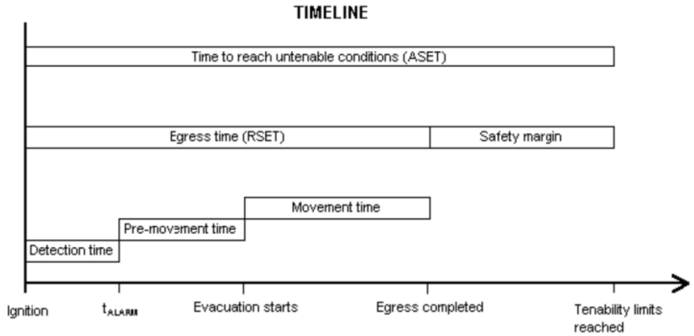

Figure 3. Diagram of "Timeline" evaluation adopted in egress safety analysis.

Among them, the available safe evacuation time ASET is the time from the occurrence of a fire to the deterioration of the fire environment that can cause serious harm to indoor personnel; The required safe evacuation time RSET is the time required for people to reach a safe area. Generally, outdoor or closed stairwells can be considered as safe areas. Generally speaking, RSET mainly depends on the export capacity, occupant load, occupant psychology and behaviour under fire, while ASET depends on the fire development, building structure, smoke exhaust measures, fire extinguishing measures, etc.

The determination of ASET is related to the tolerance limit of human body in fire. The tolerance limit of human body in a fire scenario includes many factors. This case mainly refers to foreign fire safety engineering guidelines and related literature, and adopts international standards, as follows:

- CO concentration in the area where people pass is less than 225 ppm;
- The visibility of personnel passing area is not less than 10 m;
- The radiation amount of flue gas shall not exceed 2.5 kW/m^2 (i.e. the temperature of flue gas layer shall not exceed 200 °C);
- The air temperature in the area where people pass shall not exceed 60 °C;
- When the above state is maintained in a fire scenario, it is regarded as available environment for human body.

In the fire safety analysis of this paper, the fire development, smoke flow and spread in the special space at the top of the project will be simulated and analysed by the calculation methods and simulation software, which generally accepted by the international fire engineering community, such as the field simulation software Fire Dynamics Simulator (FDS). The safety evacuation of people will also be simulated and analysed by evacuation software such as MassMotion to demonstrate the feasibility and rationality of the evacuation plan.

5.1. Design a Fire Scenario

The fire scenario design mainly considers the fire at the bottom of the sightseeing space, and considers three different working conditions: normal smoke exhaust and automatic fire extinguishing system, failure of smoke exhaust and failure of automatic fire extinguishing system. The specific fire scenarios are shown in table 1. The fire growth type is conservative according to the fast T-square fire design.

Table 1. Fire scenarios in design of sightseeing space.

Scenario number	Scenario description	Fire-extinguishing system	Fire scale	Smoke exhaust system	Purpose of scenario setting
G1	A fire is set in the middle of the bottom of the sightseeing space, four mechanical smoke outlets are set at the four corners of the top, and a natural makeup at the bottom.	Active	2.5 MW	Active	Evaluate the evacuation safety of people in the space.
G2	A fire is set in the middle of the bottom of the sightseeing space, assuming that the smoke exhaust system fails, there is no smoke exhaust port, and the bottom is provided with a natural makeup point.	Active	2.5 MW	Failure	Evaluate the safety of evacuation when the smoke exhaust system fails as extreme case.
G3	A fire is set in the middle of the bottom of the sightseeing space. Assuming that the automatic fire extinguishing system fails and the fire scale increases, four mechanical smoke outlets are set at the four corners of the top, and natural makeup at the bottom.	Failure	8.0 MW	Effective	Evaluate the safety of evacuation when the automatic fire extinguishing system fails.

5.2. Simulation Results of Smoke

Computer smoke simulation software FDS is used to simulate the design fire scenario above. According to the simulation results, it can be seen that after a fire broke out at the bottom of the high sightseeing space, the fire detection system detected the smoke at first and started the mechanical smoke exhaust system in the smoke-proof partition. Due to the high space and good smoke storage capacity, all circular platforms in the high sightseeing space can maintain a safe evacuation environment in the simulated 1200 s under normal working conditions. However, in the scenarios of G2 with smoke exhaust failure and G3 with automatic fire extinguishing system failure, the annular platform was affected by smoke at the middle and late stage of simulation. The simulation results of three fire scenarios are as shown in table 2:

Table 2. Simulation results of smoke in sightseeing space.

Scenario number	Scenario description	Available evacuation time ASET
G1	A fire is set in the middle of the bottom of the sightseeing space to simulate the normal start-up condition of the automatic fire extinguishing system and the mechanical smoke exhaust system.	Not less than 1200 s
G2	A fire is set up in the middle of the bottom of the sightseeing space to simulate the extremely unfavorable fire condition that the automatic fire extinguishing system starts normally, but the mechanical smoke exhaust fails.	707 s
G3	A fire is set in the middle of the bottom of the sightseeing space to simulate the extremely unfavorable fire condition that the mechanical smoke exhaust system starts normally, but the automatic fire extinguishing system fails.	461 s

The temperature and visibility simulation results of the designed fire scenario 1200 s are shown in figure 4.

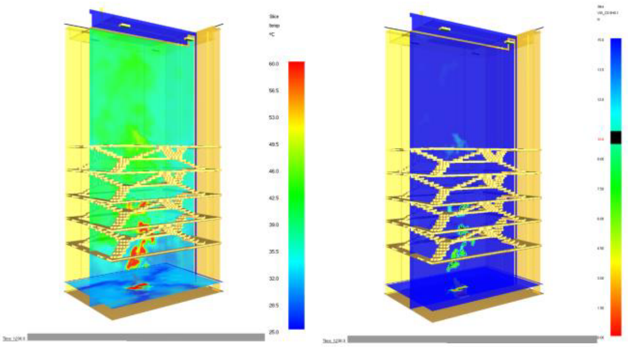

Figure 4. Slices of temperature (left) and visibility (right) of high sightseeing space profile at t=1200 s.

5.3. Human Evacuation Simulation

The MassMotion software is typically used to simulate and analyze personnel evacuation. Mass Motion software has been compared with many international standards, and has been certified or used in different international journals/seminars to ensure the reliability of its calculation [6]. The evacuation simulation analysis considers the evacuation of people in the interior space when a fire breaks out at the bottom of the high sightseeing space as shown in figure 5.

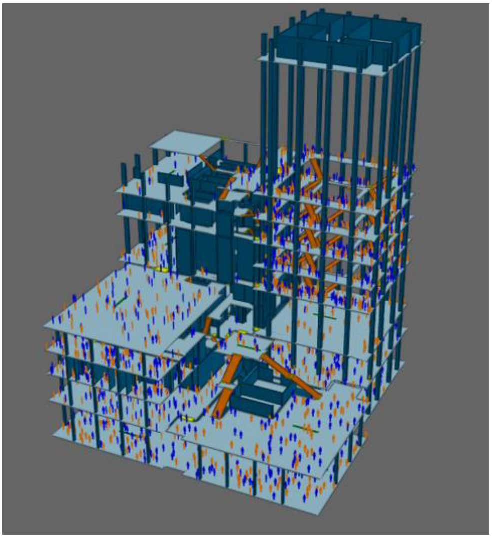

Figure 5. Human evacuation model of special space in top area.

According to the area and function of different floors of the project, it is calculated that the total number of people evacuated from the tower is about 35,000. We made use of this model to consider the evacuation of the whole building in case of emergency, and make a detailed analysis of the evacuation of the special space in the top crown area. The evacuation time of leaving the space in each horizontal loop of the sightseeing space is summarized in table 3:

Table 3. Simulation results of personnel evacuation in high sightseeing space.

Evacuation area	RSET (s)				
	Detection and alarm time	Preparation time	Evacuation action time (simulation results)		Total time (s)
			Departure time of personnel (s)	× safety factor of 1.5	
95th floor	60	60	39	58.5	178.5
94th floor			121	181.5	301.5
93rd floor			138	327	327
Whole space			138	327	327

5.4. Summary of Simulation Analysis Results of Fire Protection

According to the results of smoke simulation and evacuation simulation analysis, the available safe evacuation time ASET is longer than the required safe evacuation time RSET under the conditions of the above fire protection design scheme. In other word, for the designed fire scenarios even including the system failure condition, the safe evacuation of people in sightseeing space can be ensured, and a certain safety margin can be maintained. The results are summarized in table 4.

Table 4. Analysis results of safety evacuation of people in high sightseeing space.

Assumed condition	Available safe evacuation time (ASET)	Required safe evacuation time (REST)	Safety judgment
Both smoke exhaust and automatic fire extinguishing system are normal.	Over 1200 s	327 s	Safe
Smoke exhaust fails, and the automatic fire extinguishing system is normal.	707 s	327 s	Safe
Smoke exhaust is normal, and the automatic fire extinguishing system fails.	461 s	327 s	Safe

6. Summary

Compared to the available safe evacuation time and the required safe evacuation time, people in sightseeing space at the top of the studied super high-rise building can leave safely under different fire scenarios: the normal condition, the scenario of smoke exhaust system failure and fire extinguishing system failure. Therefore, it can be concluded that the designed firefighting strategy has a high degree of safety, and it can provide an acceptable evacuation environment for special functional places located at the top of the super high-rise tower. Taking a super high-rise building close to 500 m as an example, we analyzed the difficulties of long evacuation time and long evacuation distance in the building. A comprehensive fire design simulation demonstration was carried out in special spaces such as sightseeing in the top area of the project. The fire engineering method was adopted in the fire safety design, and the computational fluid dynamics simulation model FDS was used to analyze and simulate the smoke flow situation in the fire scenario, so as to determine the effectiveness of smoke exhaust system. The computational evacuation simulation model MassMotion was used to analyze and simulate the evacuation situation, so as to verify whether its fire egress design can also meet both the basic requirements of safe evacuation and the fire protection design requirements in the national code. The above studies have shown that the proposed fire safety can allow a safe egress of occupants at the tower top special area in this project example. The design method in this paper can be referred as a credible reference to guide the design of special use at the top of similar super high-rise buildings in the future.

References

[1] CTBUH Year in Review: Tall Trends of 2018, Tall Building Completions Maintain Momentum in 2018, The Council on Tall Buildings and Urban Habitat, Chicago. 2018.

[2] Wood A, Johnson T & Li GQ. (eds). 100 tallest buildings in the world. Proceedings of the CTBUH 9th World Congress, Shanghai. 2012; p. 902-905.

[3] Operational Considerations for Highrise Firefighting Special Report, USFA-TR-082, United States Fire Administration, Federal Emergency Management Agency. 1996.

[4] Code for Fire Protection Design of Buildings GB50016-2014 (2018 edition), China Planning Press, Beijing. 2018.

[5] Technical Requirements for Strengthening Fire Protection Design of Civil Buildings with Building Height over 250 m (Trial Implementation), Public Fire Protection (2018) No.57, The Ministry of Public Security of the People's Republic of China, Beijing, 2018.

[6] Wong HLK, Han JY, Chiou MC. Risk analysis approach of china high-speed rail tunnel evacuation design. Proceedings of the 8th International Conference on Pedestrian and Evacuation Dynamics (PED2016), 2016; p. 465-71.