Journal of Urban Development and Management
https://www.acadlore.com/journals/JUDM

Recent Fire Safety Design of High-Rise Buildings

Lizhuo Song, Jing Zhu*, Shaotong Liu, Zijian Qu

College of Civil Engineering and Architecture, College of Civil Engineering and Architecture, Harbin University of Science and Technology, 150080 Harbin, China

* Correspondence: Jing Zhu (zhujing@hrbust.edu.cn)

Received: 06-22-2022 **Revised:** 07-15-2022 **Accepted:** 08-02-2022

Citation: L. Z. Song, J. Zhu, S. T. Liu, and Z. J. Qu, "Recent fire safety design of high-rise buildings," *J. Urban Dev. Manag.*, vol. 1, no. 1, pp. 50-57, 2022. https://doi.org/10.56578/judm010106.

Abstract: As urbanization picks up speed, row upon row of high-rise buildings spring up, and their structure is increasingly complex. In the meantime, fire poses a more and more serious problem to these buildings. This paper summarizes the recent development of high-rise buildings, and analyzes the main features of high-rise building fire from the angles of material design, structural design, etc. The technical development of heat preservation material greatly improves the security of exterior fire prevention system. Starting from the structure of the building itself, architects have carried out systematic and reasonable planning for smoke exhaust design, automatic alarm design, stair design, and so on. The fire safety of high-rise buildings could be improved in an all-round way, drawing on advanced technologies like fighting drones, robots and the Internet of things.

Keywords: High-rise building; Exterior wall insulation system; Fire resistance design; Information technology

1. Introduction

Due to China's massive population and building density, multi-story and high-rise buildings account for the majority of the country's structures, and the increase in floor height and the floor area of the buildings are irreversible. High-rise structures have as a result grown like mushrooms. As shown in Figure 1, the number of high-rise buildings in China over 200 meters rose linearly between 1990 and 2018. After breaking a previous record with the completion of 147 high-rise buildings 200 meters and above in 2017, the number of such buildings increased to 143 in 2018. As of now, there are 1,478 tall buildings 200 meters and higher in existence worldwide, up from 614 in 2010—a 141% growth.

High-rise buildings are where people congregate. Once a fire occurs, it will do very serious harm to people's production and living safety [1]. At present, China has more than 340,000 high-rise buildings, with the number of super high-rise structures ranking first in the world. The safety of engineering structures under fire and explosion has become a hot and challenging topic in academia and engineering since the 9/11 terrorist attacks [2]. Over the past few decades, fire-induced collapses have occurred in high- or supertall buildings (>24 m) in different structural forms [3]. During this time, we saw the collapse of steel-framed buildings such as Buildings 1, 2, and 7 of the World Trade Center in the United States [4], the partial collapse of Windsor Tower in Spain [5], and the partial collapse of concrete buildings such as the School of Architecture at Delft University of Technology in the Netherlands [6]. In addition, we have seen that classic normative solutions fail to control smoke, such as the Cook County building in the United States [7], the Camberwell fire in the United Kingdom [8], and modern buildings using state-of-the-art fire engineering cannot control the full spread of fires, such as the CCTV Tower Fire in China and the Grinfeld Tower Fire in the UK. The collapse of WTC 7 was the first known example of a complete collapse of a tall building, mainly due to fire [9]. In 2010, a 28-story residential building in Shanghai was destroyed by a fire and 58 people died, which clearly shows that the design process did not fully consider or take into account the catastrophic consequences of the fire. The fire quickly spread through the exterior façade to the exit of the entire building. As part of a government pilot program to improve energy efficiency, the installation of external thermal insulation is a material that allows for rapid diffusion. The exterior cladding also caused fires in an apartment building in Busan, South Korea (20 minutes) and London's Greenfield Building (15 minutes) to spread rapidly throughout the building.

In China, there were over 312,000 fire accidents year between 2013 and 2019, resulting in 1,628 fire fatalities, 1,110 fire injuries, and direct property losses of up to 3.4 billion yuan. High-rise residential fire accidents are on the rise, and nearly 80% of fire-related fatalities occur in homes. Nighttime fires are particularly deadly in residential buildings, with the number of fatalities from suffocation and burning accounting for more than 70% of all fatalities in a given year, far outpacing fatalities in other types of buildings [10, 11].

A total of 252,000 fires were reported to China's public security fire department in 2020, which resulted in 1,183 fatalities, 775 injuries, and property losses of up to 4.009 billion yuan. Among them, 109,000 (43.4%) fires broke out in residential buildings. The number of residential fires in high-rise buildings totaled 6987, a significant increase of 13.6% over 2019. Overall, the fire occurrence in high-rise buildings in China is still increasing year by year.

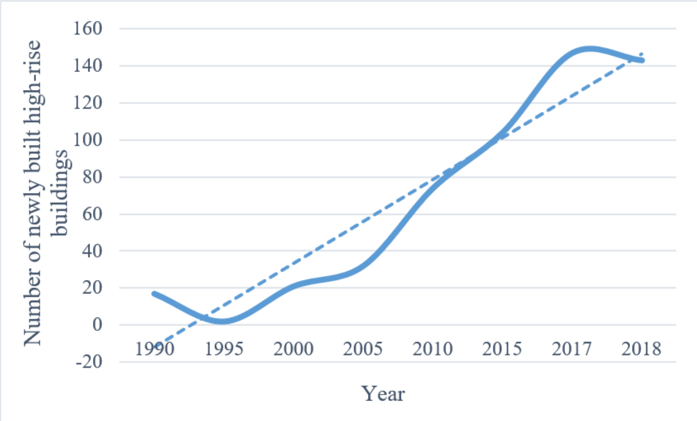

Figure 1. Number of high-rise buildings over 200 meters in China from 1990 to 2018

2. High-Rise Building Fire Features

2.1 Difficulty in Personnel Rescue

Because elevators are the primary mode of transportation inside high-rise residential buildings and most passenger elevators lack smoke and fire prevention features, it is particularly challenging to rescue people when a fire breaks out in one of these buildings. Due to the smoke pipe effect, the elevator route cannot be utilized during a fire, forcing personnel to use the fire staircases to escape to the ground. However, the fire staircases are rather narrow, making it difficult for people to leave swiftly. Those who are too late to evacuate may be endangered by the fire, and even die [12]. In addition, residents' evacuation time will be prolonged due to the building's high ceilings and large distances, and a fire disaster will inevitably be followed by smoke, which will impair residents' vision and physical well-being and raise the risk factors involved in the evacuation process. Additionally, a lot of high-rise structures have glass curtain wall enclosures. This increases the risk of damage in the event of a fire and makes rescue operations at high-rise civil construction sites very challenging [13].

2.2 Difficulty in Firefighting

In high-rise residential buildings, especially those super high-rise buildings, the fire brigade uses water guns to fight fires. But it is difficult for them to control fire effectively, because only a limited number of fire ladders are available, and their height is severely constrained. When a fire breaks out in a high-rise building, it can lead to longitudinal accumulation of flue gas in passage flue gas in stairwells, elevator shafts, and other areas. A lot of high-temperature flue gas and water vapor will build up in a small space, and the automatic firefighting systems inside the building will automatically close off the passage space. As a result, a big amount of flue gas dust cannot be promptly released, which could cause suffocation and death in personnel who are too late to leave, after inhaling a huge amount of poisonous smoke [14]. To impress viewers, typical high-rise buildings have a podium. Since the crowd is dense inside high-rise residential buildings, the firefighters have a tough time working on the podium. As the number of automobiles keeps growing, some homeowners have started parking their cars directly in the fire passage, which slows down the arrival of the fire engine and even has an impact on how firefighting operations progress [15].

2.3 Fast Spread of Fire

The majority of decorative materials used in high-rise residential buildings are combustible. When a fire arises, these materials will quickly catch fire. The fire will spread to electrical equipment, stairs, and elevators. The chimney effect of vertical pipe wells, such as stairwells, elevator shafts, and exhaust ducts, is what causes fires to start in high-rise buildings, because they have complicated internal structures [16]. The severity of flames is rising due to the smoke and fire's increased rate of circulation. This will not only inflict more damage to high-rise residential buildings, but also make firefighting and rescue operations more challenging. High-rise residential buildings also contain more exhaust ducts and pipe wells. If the proper fire prevention measures are not taken, flames will spread more quickly. In addition, high-rise buildings include a lot of combustible insulation materials and decorations, which will cause a fire to spread extremely quickly along the pipe well structure and accelerate the spread of fire smoke, directly increasing the risk of fire [17].

In this paper, the research topic of high-rise fire safety design is examined from the perspectives of material design, structural design, and advanced technology through the analysis of the fire features of high-rise structures.

3. Material Design

3.1 Classification of Insulation Materials

Currently, there are three primary categories of insulation materials used in exterior wall of buildings in China (Table 1): Inorganic insulating materials based on mineral wool, glass wool, and rock wool, which are typically considered non-combustible materials; rubber powder-polystyrene particle insulation paste-based organic-inorganic composite insulation material, which is typically referred to as a flame retardant material; organic insulating materials made of rigid foam polyurethane and polystyrene, which are typically regarded as combustible substances.

Table 1. Thermal conductivity and advantages and disadvantages of various materials

Insulation materials	Thermal conductivity/W/(m·K)	Merits	Defects
Expanded polystyrene plate (EPS plate)	0.038-0.041	Good air permeability and thermal insulation effect, cheap price	Slightly poor intensity
Extruded polystyrene board (XPS board)	0.028-0.030	Good insulation, high strength and moisture resistance	High price, pending treatment of construction surface
Rock wool board	0.041-0.045	Fireproofing and flame retardance	Large hygroscopicity, and unstable thermal insulation effect
Glue powder polystyrene particles insulation paste	0.057-0.06	Flame retardance, and low requirement at grass-roots level	Poor thermal insulation, and high construction requirements
Polyurethane foam material	0.025-0.028	Good waterproofness, good thermal insulation, and high strength	High price, poor fire resistance
Perlite and other slurries	0.07-0.09	Good fire resistance, and high temperature resistance	Poor thermal insulation, and high water absorption

3.2 Improving Combustion Performance of Organic Insulation Materials

Organic insulation materials are difficult to totally replace because of their outstanding thermal insulation qualities, superior compactness, and low thermal conductivity. However, flame retardant modification technology can be used to increase the inflammability. Both PIR and EPS insulation boards are made of the modified materials. To improve the fire safety performance of exterior wall insulation systems for high-rise buildings, China should also move faster to improve the combustion performance of organic insulation materials, develop lightweight, low toxicity, high flame-retardant organic insulation materials on an industrial scale, and reduce the application ratio of combustible insulation materials.

3.3 Developing Applicable Insulation Systems for Inorganic Exterior Walls

There is typically no significant fire safety issue when the exterior thermal insulation system of the external wall uses a flame-retardant insulation material with non-combustible or relatively low flame propagation capabilities [18]. There is a significant fire risk as a result of the widespread use of flammable polystyrene foam board (also known as polystyrene board) as a thermal insulation layer in high-rise buildings. The substantial amount of polystyrene board coverage is a key factor in the rapid spread of high-rise fire. As a result, there is not enough room between buildings for fire safety, and if a fire starts, the damage it does is unimaginable. To assure exterior insulation and flammability, it is important to promote the development and implementation of non-combustible inorganic insulating materials. In addition, high-quality insulation products are relatively backward in China. The current application proportion of this type of external insulation system in the Chinese market is very low. Facing the huge external thermal insulation market, inorganic insulation material mineral resources are relatively scarce and expensive. In addition, the technique for applying the external insulation system that uses inorganic insulating materials is insufficient [19]. Because of this, attention must be paid to the research and development of inorganic external wall insulation systems as well as the development of inorganic insulation materials.

4. Structural Design Analysis

4.1 Smoke Exhaust Design

Flue gas is the major contributor to fatalities in fires [20]. As a result, it is crucial to consider smoke prevention while designing building structures. High-rise residential buildings typically consider both natural mode and mechanical mode for their smoke prevention designs. However, during the actual design stage, the natural smoke exhaust setting is easily influenced by external negative factors, such as wind speed and terrain. Once a fire occurs, it is difficult to ensure the basic fire control effect. The natural way is primarily to use equipment such as balconies or shafts to achieve the main purpose of smoke exhaust. Mechanical smoke exhaust is the use of smoke exhaust fan equipment to carry out mandatory smoke exhaust, which can give support for the development of fire control operations. Although the effect of mechanical smoke exhaust is generally excellent, its use in high-rise structures also has downsides. As a result, the smoke exhaust method should be chosen during the actual anti-smoke exhaust design process based on the present scenario.

The first option should be natural smoke exhaust because many high-rise buildings' stairwells will have a certain heat pressure difference and the flue gas will continue to stay in the stairwell. Therefore, when designing the stairwell structure, the staff should accurately design and arrange the location and area of the window by mounting a smoke exhaust window on the wall, in order to facilitate ventilation, and choosing the smoke extraction system. The exhaust air is typically more than zero and the intake air is less than zero for the residual pressure on both sides of the building wall. When the residual pressure is zero, the window hole's upper and lower halves can be employed as the intake and exhaust areas, respectively. The residual pressure-zero plane can also be used as the neutralization surface. In this regard, it is necessary to install windshields in the upper portion of the middle and middle surfaces, and exhaust air windows in the lower portion of the middle and surfaces, during the design phase. The air temperature differential between inside and outside will cause a heated pressure to develop. In the design process, the difference between internal and external pressure on the window is the total of hot pressure and wind pressure, for the difference in pressure and density will cause the flow of inside and outside air, hot pressure and wind pressure will influence high-rise buildings. To integrate mechanical smoke exhaust and natural smoke exhaust efficiently, windows should be set up for the patio as well as smoke-proof stairs and fire elevators inside high-rise residential structures [21]. For instance, it is possible to build an air supply system at the evacuation staircase and a smoke extraction system in front of the elevator. The smoke extraction system, a crucial component of high-rise structure fire safety, can be used to its maximum economic and practical advantage, during the design of the smoke extraction system in high-rise buildings.

4.2 Automatic Fire Alarm System

Due to the increasing number of high-rise structures, various functions, and sophisticated fire automated alarm system, fire automatic alarm system plays an indispensable role in fire advance forecast, timely firefighting, personnel evacuation, and preventing the spread of fire. Its intricacy is demonstrated by the numerous detection and control points as well as the intricate control logic. Fire hydrant fire extinguishing system and automatic sprinkler system linkage control design are included in fire automatic alarm system fire linkage control design. The main objective of the fire hydrant fire extinguishing system design is to ensure that the system controls the linkage start and stop of the fire pump, with the aim to effectively control the fire situation before the fire grows larger and spreads. The manual start and stop of the fire pump, the status display of the fire pump, and the button for the location of the fire hydrant to start the pump are additional features of the fire extinguishing system design that can be easily handled under various circumstances or in the event of a failure [22]. For instance, according to the Ryusan channel, the walking distance from any position inside a fire zone to the closest manual fire alarm button should not be more than 30m. The entry and exit points, as well as any other portions that are obviously simple to use, technological alarm zones or fire protection partitions, should have the fire display disk installed. Each floor's landing, the front chamber of the fire elevator, the internal corner of the building, etc. should all have sound and light alarms installed in prominent locations. There are emergency broadcast stations put up in public areas like hallways and lobbies. The number of speakers should be sufficient to keep the distance from any section of a fire zone to the nearest speaker under 25 meters (m), and the distance from the nearest speaker at the end of the pathway under 12.5 meters (m). Each speaker's rated power shall not be less than 3 watts.

4.3 Safe Evacuation Design

The staircase needs to be renovated and fortified first. The size of the fire prevention and evacuation ability of the stairs directly impacts the safety of personnel and the disaster relief work of firefighters. Stairs are a common evacuation tool and are often the first route of escape that people consider. For this reason, the building fire protection design should be based on the type of use of the building, height, number of floors, proper application of various building standards, and selection of evacuation stairs that meet the fire protection requirements in order to create favorable conditions for a safe evacuation. The stairwell can be classified into four types based on the fire safety requirements: open stairwell, closed stairwell, smokeproof stairwell and outdoor auxiliary evacuation stairs.

The general requirements are as follows:

1. The layout of the stairwell should ensure a safe evacuation distance and, to the greatest extent possible, prevent the formation of bag-shaped walkways.
2. To enable two-way evacuation, the stairwell should be placed adjacent to the ends of the standard floor or fireproof partition.
3. Place against the exterior wall to allow for natural ventilation, lighting, and firefighter rescue operations.
4. The position of the evacuation stairwell on each floor, straight up and down, and the position should not be changed, with the exception of the stairs leading to the basement and the stairs leading to the misaligned evacuation floor in the super high-rise structure. There should be a door leading directly outside on the ground floor. If the placement of the stairwell changes, it will be challenging for staff to locate the steps in an emergency, lengthening the evacuation time and increasing the risk of unnecessary casualties, particularly in public buildings like hotels, restaurants, and commercial structures.

Second, the evacuation of the roof is just as crucial as the evacuation from the ground. High-rise buildings should be designed with a helipad at the top level to provide for quick transportation and evacuation of stranded persons on the top floor.

Finally, a reasonable evaluation layer needs to be set up. When a fire problem arises, a room can be provided for residents to wait for assistance in a relatively safe spot, effectively reducing casualties. It is also important to make sure the evacuation level is spacious enough to accommodate individuals and is well-equipped.

Optimizing the pathway design should come first while working on horizontal evacuation designs. The aisle should be adequately set up with fire safety devices and design lighting [23]. Second, create fireproof stairwells, make sure the design is humane. For senior people with weak legs and feet, use the method of creating ramp-style evacuation stairs [24]. Third, it is not appropriate to share the stairway with the upper floor; there should be fireproof separation measures between the basement and semi-basement stairs and the first floor. On the first level, a partition wall with a fire resistance limit of no less than 2 hours should typically be utilized to divide into different areas and lead straight to the outside. A Class B fire door should be utilized whenever doors that are part of the partition wall need to be opened. The basement and semi-basement stairwell's first floor should lead directly to the exterior to ensure the quick evacuation of personnel. In order to successfully prevent evacuees from accidentally entering the basement or semi-basement as well as to stop the spread of fire and smoke, fire separation facilities must be available in the first floor stairway as well as the basement and semi-basement.

5. Advanced Technology Analysis

5.1 Drone Technology

Unmanned aerial aircraft, which are currently a crucial piece of auxiliary equipment for firefighting and rescue, have the intellectual advantages of precise positioning and flight direction, visual tracking, and obstacle avoidance. Drones can operate in hazardous fire environments, protect firefighters' personal safety, and carry out search and rescue operations in locations that are inaccessible to firefighters. The UAV's infrared camera makes it easy to gather images at night, monitor heat sources, and carry out fire rescue operations. The UAV can fly and hover at a fixed position while employing the video image tracking feature to capture the real-time dynamics of the fire scene. Additionally, the UAV is lightweight, highly flexible, simple to use, and portable. Drones and remote sensing technology work together to improve image acquisition in fire regions, giving firefighters enough time to escape [25]. The performance and volume of UAVs in China are currently mature and stable, and the country has a wide range of UAV development types. UAVs have a wide range of potential applications in rescue and firefighting. The functionality of UAVs has been significantly expanded, and domestic UAV models have a powerful information transmission capability that can implement information transmission between satellites [26]. The JTIS24F-6 firefighting drone is depicted in Figure 2.

Figure 2. JTIS24F-6 firefighting drone

5.2 Firefighting Robot Technology

China started researching fire robots in the 1970s. With the constant advancement of science, technology, and technical infrastructure, the field of fire robot research and development has now reached a new level. In the event of a fire mishap, firefighting robots must be able to accurately assess the environment, gather and analyze information and data in a secure area, and establish the location of the fire source and the cause of the fire through analysis and judgment [27]. In risky fire conditions, using firefighting robots instead of people to do rescue operations may become more prevalent. effectively lessen the challenges of rescue. Currently, firefighting robots are evolving in the direction of automation and intelligence, and China is aggressively importing cutting-edge foreign robot technology. As a result, these robots are becoming ever-more-perfected in accordance with the unique circumstances and technical level in China (Figure 3).

Figure 3. RXR-MC80BD-TG61 firefighting robot

5.3 IoT

With the advancement of computers, the use of IoT technology to produce intelligent fire protection has progressively emerged as a powerful method of resolving complex fire protection issues. The traditional fire protection system's equipment and facilities are connected to the fire IoT system's sensing, communication, and other technologies through social fire supervision and management, i.e., the public security organizations participating in firefighting and rescue operations, and other technologies. This is meant to create a basic environment for high-sensitivity fire protection, which achieves real-time, dynamic, interactive, integrated fire information collection, transmission, and processing, as well as promoting and improving the government and related agencies to implement the social fire supervision and management [28]. It will also significantly improve the command, dispatch, decision-making, and disposal capabilities of public security organs that deal with firefighting and rescue.

The IoT system's ability to connect the physical and digital worlds depends on the research and development of sensor devices. The fire IoT system's sensing apparatus must be flexible enough to work with a range of front-end sensing components while also being simple to install and maintain. Installation of sensing equipment, an IoT access unit to link multiple sensor types, gather sensor signals, keep track of device switch status, and transmit data are required to monitor the location's fire water level, water pressure, voltage, current, door switch, and other states. Cameras for monitoring the condition of the work in the fire duty room, as well as the consumption of important monitoring components, are put in the ceiling or higher on the wall. The door switch sensor, which is fixed to the lower edge of the fire door frame, monitors the opening and shutting status of the building's fire door, and the ring hole card is installed on the equipment distribution wire; When the concentration of combustible gases is greater than the concentration of air, combustible gas detectors are placed underneath the pipeline and storage tank. When the concentration of gases is less than the air, they are placed on top, and the barometric pressure sensor tank and the pipeline are installed inside the pipe and the tank to collect gas pressure data.

The use of fire Internet of Things can rely on big data to compare the fire forces around the fire point, truly show the current actual situation of the nearby fire fighting force, the automatic cruise function of the smart fire Internet of Things can help rescuers save more time, mainly reflected in the rescuers can avoid the time to investigate, find the fire source, and have more time to the scene to carry out rescue. The fire rescue team uses a dedicated emergency rescue mobile terminal, and the distribution of fire fighting forces is clearly displayed on the map. After the fire broke out, the whole fire department formed a linkage command system, and in the entire fire linkage command system, the information was interconnected. The team dedicated to rescue command can realize visual and dynamic command and dispatch throughout the fire rescue scene.

6. Conclusions

(1) In the current process of urbanization, construction, and development, the proportion of high-rise buildings in the total number of buildings is steadily rising. External thermal insulation and fire prevention of high-rise buildings will not only have a more serious impact on the safety of high-rise residential residents' lives and property, but will also play a key role in the future development and construction of the city. To improve external thermal insulation and fire prevention, it is extremely important to promote the research and development of non-combustible and refractory insulating materials, as well as their widespread application.

(2) As science, technology, and networks continue to advance, firefighting and rescue have also taken on a variety of forms. Real-time firefighting IoT monitoring and high-research and development of fire UAVs and robots have significantly lowered the difficulty of rescuing fire fighters. Furthermore, the security of fire fighters has been carefully maintained. It has taken some time for the research and development effects of new technologies for high-rise building firefighting and rescue to become apparent, and there is still much to be done to fully informatize fire rescue, fire supervision, and fire management.

(3) The intelligent fire Internet of Things system is a product of the information age, and in its system architecture, the perception layer is the source of obtaining information data. The core key of the perception layer is the detection technology, and the performance of the detector determines whether the fire Internet of Things system can operate accurately, objectively and well. In the existing fire protection system, the "perception layer" in the architecture is served by the smoke temperature detector, flame detector, gas detector and other monitoring equipment of the fire protection system, and the equipment transmits fire information and system operation status by detecting physical signals such as temperature, light smoke, flame radiation, and air pressure. However, the sensitivity and automation of detectors, pressure switches and other equipment in the current fire protection system cannot fully meet the requirements for detectors in the fire Internet of Things system. As well as the lack of necessary intelligent analysis and evaluation, the upgrading and improvement of the system is also the focus of future research and development. Therefore, in the next development of the fire Internet of Things, it is particularly important to break through the core technology, upgrade the software system, and improve the accuracy and automation of the detector.

Fundings

This research was supported by the National Natural Science Foundation of China (Grant No.: 51508140); the Natural Science Foundation of Heilongjiang (Grant No.: LH2019E066).

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] X. X. Chen and C. Tang, "Analysis on fire safety status of high-rise buildings and research on fire prevention and control countermeasures," *Fire. Protect. Tod.*, vol. 4, no. 8, pp. 36-37, 2019.

[2] H. Chen and J. Y. Liew, "Explosion and fire analysis of steel frames using mixed element approach," *J. Eng. Mech.*, vol. 131, no. 6, pp. 606-616, 2005. https://doi.org/10.1061/(ASCE)0733-9399(2005)131:6(606).

[3] A. Cowlard, A. Bittern, C. Abecassis-Empis, and J. Torero, “Fire safety design for tall buildings,” *Procedia. Engineer.*, vol. 62, pp. 169-181, 2013. https://doi.org/10.1016/j.proeng.2013.08.053.
[4] “Final report on the collapse of the World Trade Center towers,” NIST-NCSTAR-1, 2005, Gaithersburg, MD, US: National Institute of Standards, & Technology.
[5] D. Parker, “Madrid tower designer blames missing fire protection for collapse,” *New. Civil. Engineer.*, vol. 2005, pp. 5-7, 2005.
[6] B. Meacham, M. Engelhardt, and V. Kodur, “Collection of data on fire and collapse, faculty of architecture building, delft university of technology,” *In Proc of NSF Engineering Research and Innovation Conference*, (ERIC 2009), Honolulu, Hawaii, 2009, ResearchGate.
[7] D. Madrzykowski and W. D. Walton, *Cook County Administration Building Fire, 69 West Washington, Chicago, Illinois, October 17, 2003: Heat Release Rate Experiments and FDS Simulations*, US: US Department of Commerce, National Institute of Standards and Technology, Building and Fire Research Laboratory, 2004.
[8] “Report to the secretary of state by the chief fire and rescue adviser on the emerging issues arising from the fatal fire at lakanal house,” 09-CFRA-06065, 2009, Camberwell: Department for Communities and Local Government.
[9] “Final report on the collapse of the World Trade Center Building 7,” NIST-NCSTAR-1A, 2008, Gaithersburg: National Institute of Stand-ards and Technology.
[10] “Fire Data Statistics 2013-2019,” LY-T-1627-2020, 2020, China: Fire and Rescue Bureau, Ministry of Emergency Management.
[11] Y. Wang, S. L. Shi, R. Q. Li, Y. Liu, and X. Y. Chen, “Statistical analysis and countermeasures of national fire accidents from 2013 to 2016,” *Safety.*, vol. 39, no. 11, pp. 60-63, 2018.
[12] G. B. Li, “Analysis of fire safety status of high-rise buildings and research on fire prevention and control countermeasures,” *China. Residential. Facilities.*, vol. 2019, no. 4, pp. 73-74, 2019.
[13] J. C. Bai and L. Shang, “Problem analysis and countermeasures on fire protection design of high-rise civil buildings,” *Architecture. and Cult.*, vol. 2020, no. 5, pp. 212-213, 2020.
[14] S. Y. Chen, “Analysis and countermeasures of fire protection design problem of high-rise civil buildings,” *Fire Prot. Circle*, vol. 5, no. 14, pp. 26-27, 2019. https://doi.org/10.16859/j.cnki.cn12-9204/tu.2019.14.013.
[15] K. Zhang, “Exploration of prefabricated prefabricated building design practice and engineering technology innovation of high-rise residential buildings,” *Housing. and Real. Estate.*, vol. 2020, no. 24, pp. 80-80, 2020.
[16] L. Zheng, “Some thoughts on the design of smoke prevention and exhaust of high-rise buildings,” *Fire Technolo. and Product Inform.*, vol. 2017, no. 3, pp. 21-22, 2017.
[17] Q. L. Meng, “Analysis and countermeasures of fire protection design of high-rise civil buildings,” *Shanxi Archit.*, vol. 46, no. 20, pp. 195-196, 2020. https://doi.org/10.3969/j.issn.1009-6825.2020.20.076.
[18] W. Y. Zhang and Y. Q. Wang, “Fire hazards and fire countermeasures of building exterior wall insulation engineering,” *Fire Prot. Technol. and Product Inform.*, vol. 2013, no. 5, pp. 3-7, 2013. https://doi.org/10.3969/j.issn.1002-784X.2013.05.001.
[19] S. H. Lai, “Discussion on fire prevention measures for external wall insulation system of high-rise buildings,” *J. of Armed Police College*, vol. 29, no. 4, pp. 52-54, 2013.
[20] H. C. Ding, Y. D. Xu, Q. L. Deng, and Z. X. Lian, “Simulation study on influence of fire smoke flow on evacuation in high-rise buildings,” *China Safety Science J.*, vol. 30, no. 12, pp. 118-124, 2020. https://doi.org/10.16265/j.cnki.issn 1003-3033.2020.12.017.
[21] L. H. Mai, “Discussion on the application of green building design in residential building design,” *Eng. Technol. Res.*, vol. 5, no. 14, pp. 202-203, 2020.
[22] Y. Xie, “Design and analysis of automatic fire alarm system for high-rise civil buildings,” *Jiangxi Build. Materi.*, vol. 2021, no. 11, pp. 121-122, 2021.
[23] Z. M. Huang, “Research on fire protection design problems and countermeasures of high-rise civil buildings,” *Fire. Protect. Tod.*, vol. 6, no. 11, pp. 94-96, 2021.
[24] L. D. Huang, K. Z. Luo, Y. Liu, J. J. Xu, X. X. Xu, and X. C. Wang, “Crowd evacuation simulation of fire scene in elderly apartment,” *Chinese J. of Safety Science*, vol. 30, no. 3, pp. 137-142, 2020. https://doi.org/10.16265/j.cnki.issn1003-3033.2020.03.021.
[25] J. T. Li, “Application of unmanned aerial vehicle in firefighting and rescue work,” *Today Fire*, vol. 5, no. 7, pp. 25-26, 2020.
[26] X. C. Li, “Application of unmanned aerial vehicles in chemical firefighting and rescue work,” *China Broadband*, vol. 2021, no. 3, pp. 74-74, 2021.
[27] X. Q. Peng, “Application status and prospect analysis of firefighting robot in China's firefighting and rescue,” *Fire Today*, vol. 4, no. 12, pp. 18-19, 2019.
[28] J. F. Hu and N. Ding, “Research on the application of internet of things technology in smart fire protection,” *Electr. World*, vol. 2019, no. 2, pp. 194-196, 2019.