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Fire Risks in High-Rise Buildings: A Critical Review of Mechanisms, Impacts, and Technical Management Challenges

Meng Donggang[1,2,*], Norhaiza Nordin[1]

[1]Kuala Lumpur University of Science and Technology, Kajang, Malaysia

[2]Guangxi University of Science and Technology, Guangxi, China

[*] Corresponding Author

Abstract

The growing size and complexity of high-rise buildings pose significant challenges to fire safety worldwide. This review synthesizes recent global trends in high-rise buildings and analyzes the evolving risk landscape associated with fire incidents. It systematically explores the mechanisms of fire development and vertical spread, followed by a detailed assessment of the multi-faceted impact of building fires on life safety, structural integrity, property safety and environmental health. Based on a combination of statistical data and the latest literature, this paper identifies key technical management deficiencies in the construction and operational phases that lead to the accumulation of fire risk. Despite advancements in smart fire protection technology, there is still a lack of a comprehensive technical management framework based on the life cycle. This paper concludes by highlighting the need for future research, particularly the development of integrated strategies for fire prevention, early detection, coordinated evacuation, and post-event recovery in high-rise environments.

Keywords

High-rise buildings, Fire risk, Fire development, Structural safety, Fire impacts, Technical management

1. Introduction

With the global urbanization, the number of high-rise buildings has soared, and characteristics such as complex spatial structures, high population density, and vertical evacuation paths have exacerbated the fire risk (Dabous et al., 2024; Year in Review 2023, 2024). Compared with low-rise buildings, high-rise buildings are more prone to vertical fire spread, slow evacuation, and significant loss of life and property(Li, 2024).

Existing problems often stem from systemic flaws such as inadequate integration of fire protection measures during construction, poor enforcement of technical standards, and weak supervision (Kodur et al., 2020a; B. J. Meacham, 2023). Despite the development of technologies such as Internet of Things (iot) alarm systems and BIM-supported evacuation modeling, their application remains uneven across regions (Mohammadiounotikandi et al., 2023a).

This paper systematically reviews the fire risk in high-rise buildings from a life cycle perspective, focusing on fire development mechanisms, multi-dimensional impacts, and technical management deficiencies, integrating cross-national research results, and identifying areas that urgently need in-depth research in the future.

2. Development and Fire Risk Trends in High-Rise Buildings

Global city skylines have changed significantly over the past few decades due to the rapid increase in high-rise and super high-rise buildings. This verticalization trend, driven mainly by

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urban population growth, tight land resources and the need for integrated spatial functions, has not only reshaped urban architectural forms but also brought new fire safety challenges. Compared with low-rise buildings, high-rise buildings face more complex evacuation routes, higher fire loads and the risk of fire spread from combustible facade materials in the event of a fire, significantly increasing the disastability of fire incidents. At the same time, due to the limitations of current fire statistics in terms of height classification, data integrity and regional comparability, a comprehensive understanding of the fire risk in high-rise buildings is restricted.This section will start from the global trends in high-rise buildings, analyze the new paths of fire risk evolution they bring, focus on the challenges to fire management strategies posed by trends such as mixed-function Spaces and high-density cities, and aim to provide a data background and risk mechanism understanding framework for subsequent research, emphasizing the urgent need for high-rise building fire management to shift towards a more refined, dynamic and data-driven path.

2.1. Global Development and High-Rise Fire Incidence

Over the past decade, global high-rise buildings have grown rapidly. According to CTBUH (2023) data, as of 2023, A total of 2,441 buildings of 200 meters and above and 241 super high-rise buildings of 300 meters and above have been built globally. The first 100 super high-rise buildings were completed in 2015, and the remaining 141 were completed in the following seven years. in addition, the first 1,000 200-meter and above buildings were completed in 2015, and that number has now more than doubled(Year in Review 2023, 2024). In parallel with this trend, however, there has been an increase in high-rise building fires. High-rise building fires are more likely to cause casualties and property damage than low-rise ones due to the difficulty of vertical evacuation, delayed emergency response and flammability of facade materials(Salankar, 2021; Tracy et al., 2023).

2.2. Patterns in Fire Risk and Statistical Uncertainty

Despite the regular release of fire statistics by NFPA and national fire agencies, there are obstacles to comprehensive risk identification due to inconsistent classification criteria, underreporting of data in developing countries, and the fact that most statistics do not distinguish between high-rise buildings. For example, the proportion of deaths due to smoke inhalation in high-rise fires is often overlooked, and there is a lack of tracking records of exterior wall spread incidents, creating blind spots in the study of the unique risk characteristics of high-rise buildings (Mashayekh, 2020; Yuen et al., 2021).

2.3. Emerging Trends in Urbanization and Fire Load

As cities become more densely populated, high-rise buildings that combine residential, commercial and hotel functions are becoming more common, and the types of fire loads and the patterns of people's use are becoming more complex. This trend places higher demands on dynamic modeling of fire risk and phased management strategies, yet most of the current codes are still based on static building models and lack a systematic response mechanism for mixed spatial structures(Gernay, 2024; Oaikhena & Akande, 2024)

3. Fire Development Mechanisms and Spread Dynamics

Understanding the causes, development and spread mechanisms of fires in high-rise buildings is crucial for effective risk reduction. Unlike low-rise buildings, high-rise environments introduce complex thermal, spatial, and material dynamics that significantly alter fire behavior. Factors such as the vertical continuity of combustibles, insufficient fire compartments, and the use of modern synthetic materials contribute to the accelerated spread of flames and the production of dangerous smoke. At the same time, existing fire modeling methods often fail to

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capture the typical nonlinear development processes and interactions between multiple floors in high-rise buildings. This section will critically examine the key stages of fire development, vertical spread mechanisms, material effects, and modeling challenges to provide insights into the unique fire dynamics of high-rise buildings.

3.1. Stages of Fire Development in Buildings

Building fires typically go through four stages: ignition, growth, full development, and decay (Khan et al., 2023). Although such divisions have been widely adopted, most modelling methods do not adequately model the nonlinear evolution of fires in high-rise buildings. For example, the risk of a fire rapidly transitioning from the growth stage to the full development stage is seriously underestimated due to insufficient vertical combustible continuity and partitioning (Li, 2024).

3.2. Vertical Spread and Heat Transfer in High-Rise Buildings

The vertical spread of flames and smoke along shafts, pipes, stairwells, etc. is one of the most dangerous and least studied phenomena in high-rise building fires. Although the mechanisms of thermal convection and radiation have been widely recognized, there is still a lack of quantitative research on the effects of shaft geometry, ventilation systems, and fire containment measures on the upward spread of fire. Most current codes also lack specific operational provisions for vertical spread (Yuen et al., 2021).

3.3. Influence of Materials and Structural Systems

The role of modern building materials in fire development remains controversial. Although traditional materials such as concrete have some passive protection capabilities, lightweight composite panels, aluminum-plastic panels and synthetic insulation materials often cause the fire to spread faster and toxic smoke to be released. Most studies have examined the performance of the materials without considering the interaction of ventilation, facade construction and aging factors, and the degradation performance of fireproof coatings and sealing materials under long-term thermal cycling (Yuen et al., 2021).

3.4. Critical Gaps in Fire Spread Modeling

Despite the extensive use of simulation tools such as FDS and PyroSim for fire modeling, parameter calibration for high-rise environments remains significantly inadequate. Most models use ideal boundaries, steady-state ventilation, and simplified smoke layer Settings, lacking real-scale validation, resulting in significant differences between simulated paths and actual fire in buildings with open atriums or connected floors(Qi et al., 2024).

4. Impacts of High-Rise Building Fires

High-rise building fires have wide-ranging impacts in terms of casualties, structural damage, economic loss and environmental pollution, and their catastrophic effects are exacerbated by building height, functional density and the difficulty of emergency response. This section systematically explores the multi-dimensional impact mechanisms of high-rise building fires from four dimensions: life safety, structural resilience, property damage, and ecological risk.

4.1. Impacts on Life Safety

High-rise building fires pose a serious threat to life safety due to long evacuation paths, vertical spread of smoke, and accumulation of toxic gases. The combined effect of thermal radiation and carbon monoxide leads to a significant increase in mortality in confined or high-density floors (Dubinin et al., 2020). Studies show that more than 70 percent of fire deaths result from smoke inhalation rather than direct burns (Loke et al., 2020).

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The elderly, children and people with limited mobility are the most vulnerable groups due to their limited ability to escape. Whether stairwell arrangements, smoke blocking measures and alarm systems can be activated within the "five-minute golden period" directly determines the success rate of escape(Gerges et al., 2022)

Panic, misjudgment and congestion of people during a fire often exacerbate casualties. Relevant research highlights the important role of evacuation signs, voice alerts and training education in suppressing irrational behavior and improving survival rates. In addition, survivors often have long-term psychological effects such as post-traumatic stress disorder (PTSD) and anxiety (Gerges et al., 2022).

In recent years, smart fire protection systems and Internet of Things-based evacuation assistance technologies have shown promising prospects in real-time evacuation guidance and location of trapped people (Mohammadiounotikandi et al., 2023b). but their popularity in old buildings and poorly regulated areas remains limited.

To sum up, ensuring life safety in high-rise building fires requires coordinated efforts in multiple dimensions such as design, alarm response, evacuation organization and personnel preparation, and relies on the dual guarantee of technical support and continuous training.

4.2. Impacts on Structural Safety

Fires have a significant impact on the load-bearing capacity of building structures. At high temperatures, steel strength drops rapidly, concrete may crack and flake off, and composite structural systems have an unpredictable risk of degradation(Hopkin et al., 2021; Kodur et al., 2020b). In high-rise buildings, columns and junctions are more prone to instability under the effect of thermo-mechanical coupling ((American Society of Civil Engineers, 2020)

The extent of structural damage depends on the duration of the fire, the fire and heat insulation performance, and the redundancy of the structural system. Insufficient thickness of the fireproof layer or improper maintenance can accelerate structural failure ((Gernay & Khorasani, 2020; B. Meacham & McNamee, 2020).

In recent years, the development of performance-based fire design (PBFD) and structural health monitoring technologies has enhanced the predictive and response capabilities for fire damage(Siddiqui et al., 2021). , but the scarcity of real-scale fire test data for high-rise buildings still limits the practical application of the model.

Post-fire safety assessment should not only focus on visible deformation but also identify hidden material damage and residual stress, which may pose long-term safety hazards if there is a lack of scientific repair ((Dashti et al., 2025; Mostofi et al., 2024).

In summary, the integrity of high-rise building structures in the event of fire depends on active fire protection design, reliable passive protection measures, and intelligent monitoring systems to achieve the goal of continuous safe operation.

4.3. Property Loss and Economic Consequences

Due to their large scale, dense population and concentrated assets, high-rise building fires often cause severe property damage. Fires often spread across multiple floors, damaging interior decoration, structural components and critical systems such as HVAC, resulting in high direct repair costs and long-term business disruptions (Rahman et al., 2023).

Indirect economic losses cannot be ignored either, including business suspension losses, rent interruption, relocation costs and increased insurance premiums. Especially in mixed-use high-rise buildings such as commercial complexes and office buildings, the chain effect can affect the entire supply chain system (Gernay & Khorasani, 2020).

The study also pointed to underinsurance in many regions, especially in developing countries, where actual fire losses often exceed the coverage. In addition, aging fire extinguishing systems

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and incomplete asset information also hinder the efficiency of risk assessment and post-disaster recovery efforts.

Therefore, enhancing the economic resilience of high-rise buildings to fire requires not only a passive protection system, but also enhanced financial planning, asset recording and insurance coverage in the early stage, and the integration of loss control mechanisms into the technical management strategy throughout the building's life cycle.

4.4. Environmental Impact and Pollution Risks

During fires in high-rise buildings, the burning of synthetic insulation materials, plastics, and coating surfaces releases large amounts of toxic pollutants such as dioxins, polycyclic aromatic hydrocarbons (PAHs), and fine particulate matter (PM2.5), causing significant harm to air, water, and soil environments (Jakhar et al., 2023).

Fire plumes can spread over large urban areas, especially in densely populated downtown areas, causing immediate and long-term effects on air quality. Residual ashes and fire-fighting wastewater may contain heavy metals and other toxic components that enter the drainage system or seep into the soil, causing persistent environmental pollution (Kodur et al., 2020).

The post-fire clean-up and demolition process also generates large amounts of construction waste, some of which cannot be recycled due to chemical contamination. However, most fire assessments still focus on life and structure, ignoring the economic and technical costs of environmental restoration.

At present, most fire protection regulations lack environmental protection standards, and there is a lack of connection between fire protection planning and environmental risk control, especially in large cities with dense high-rise buildings, which seriously affects the effectiveness of post-fire treatment.

To address these deficiencies, fire management strategies urgently need to incorporate pollution control, environmental monitoring and sustainable material selection, and embed the concept of environmental resilience at the architectural design stage. Only by integrating the environmental protection mechanism system into the fire protection engineering system can the future-oriented urban safety development goals be achieved.

5. Technical Management Challenges Across Lifecycle Phases

Effective fire safety management in high-rise buildings needs to be implemented throughout the entire life cycle from construction to operation. However, persistent flaws in technical implementation, information transmission and regulatory mechanisms have severely restricted the achievement of safety goals. This section sorts

out the core management issues at each stage and emphasizes the necessity of building an integrated life cycle risk governance system based on digital platforms.

5.1. Construction Phase Issues

During the construction phase, fire risks often stem from inadequate implementation of design drawings, lax enforcement of fire protection regulations, and insufficient supervision of temporary fire protection measures. Welding, cutting and other hot work operations often fail to strictly follow safety regulations, which can easily trigger fire sources (Wang, 2023). In addition, the lack of coordination among the construction party, the design party and the acceptance party, as well as the ambiguous responsibility interface, can also lead to the neglect of fire hazards.

5.2. Operation and Maintenance Phase Issues

After the building is put into use, ongoing fire safety depends on daily maintenance, regular inspections, and system operational integrity. However, studies have found widespread

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problems such as outdated fire protection equipment, failed alarms, and inadequate personnel training (B. J. Meacham, 2023). Many smart fire protection systems fail to truly perform their early warning and linkage functions due to the lack of data feedback mechanisms or low integration.

5.3. Cross-Phase Transition Challenges

The transition phase from construction to operation is crucial but often overlooked. Common problems include incomplete technical documentation, missing system commissioning records, and the absence of a responsibility transfer mechanism, which leads to information breakages and fire management responsibility idling(Chang & Parlikad, 2024). This poor connection severely undermines the system's emergency preparedness and operational reliability.

5.4. Need for Lifecycle-Based Integrated Management

The lifecycle fire management model emphasizes the integration and unification of information at various stages such as design, construction, and operation to achieve traceable decision-making, adaptive upgrades, and continuous monitoring. Digital tools such as BIM, Internet of Things sensors and data platforms provide technical support, but are not widely applied in most projects (Olaseni, 2020; Rane et al., 2023).

6. Discussion and Future Research Directions

As urban density, building complexity and technological coupling continue to rise, fire safety governance in high-rise buildings is shifting from passive response to active prevention and control. Based on the previous analysis of fire mechanisms, impacts and management challenges, this section will delve into the causes of current systemic failures, propose the necessity of building an integrated life-cycle technology management system, and further clarify the key directions for future research.

6.1. Summary of Key Risk Mechanisms and Systemic Challenges

This study shows that the fire risk in high-rise buildings is not a single technical error, but a systemic defect throughout the entire process of design, construction, operation and maintenance, and management. These include problems such as the lack of fire integration in the early design stage, inadequate supervision in the construction stage, insufficient maintenance investment in the operation stage, and unclear responsibility in the transition between stages. Minor oversights such as the absence of fire seals or inadequate alarm tests can easily cause a chain reaction and lead to major disasters in actual fires.

6.2. Integrated Technical Management Framework Needs

To address the fragmentation and passive response of the current management system, there is an urgent need to build a lifecycle oriented technical management framework. The framework should include a fire review mechanism for the design phase, a dynamic supervision and measure list for the construction phase, a digital handover process for the commissioning phase, and an Internet of Things-based facility operation and maintenance platform. In addition, policy support and cross-disciplinary collaboration among design, engineering, construction, supervision, etc. will be relied upon.

6.3. Research Gaps and Future Study Areas

Several key issues remain to be explored in depth, including:

•Construction of a quantitative propagation model for life-cycle fire risk in high-rise buildings;

•An empirical Study on the actual Effectiveness of intelligent systems and AI-assisted evacuation platforms;

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•Long-term case Studies of Failure mechanisms in the construction-operation transition phase;

•Simulation Verification of the integrated fire management framework in real projects;

•Research on Multi-party Collaborative Behavior and Decision-making Mechanisms in Fire Emergency Scenarios.

7. Conclusion

This study systematically reviews the global development trends, fire statistics, spread mechanisms and multi-dimensional impacts of fire risks in high-rise buildings, revealing the systematic characteristics of fire protection issues in high-rise buildings. The study shows that fire risks often stem from the fragmentation and disconnection of management at various stages of life cycle (design, construction, operation, handover)

The main findings of the study include:

•High-rise building fires show characteristics such as rapid vertical spread, difficult evacuation and increased impact on vulnerable groups;

•Structural failures caused by fires are progressive and closely related to improper material selection and maintenance;

•The property, economic and environmental damage caused by fires is more severe in high-density urban environments;

•Technical management deficiencies, especially during the construction and operation and maintenance phases, are the main source of safety failures.

Research shows that life-cycle-oriented fire safety management is crucial. This requires integrating fire safety protocols into every stage with the support of digital technologies such as BIM and the Internet of Things. Interdisciplinary coordination and policy reforms are also crucial for promoting forward-looking risk governance.

Future research should focus on building empirical datasets, validating fire risk models, and piloting integrated technology management systems in actual projects to support data-driven decision-making and policy-making.

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Conflict of Interest

The authors declare no conflict of interest.

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