DOI:10.5937/IIZS26489B

FIRES IN HIGH-RISE BUILDINGS: ANALYSIS OF FIRE SAFETY AND ENGINEERING ASPECTS

Review paper

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Abstract: Fires in high-rise buildings represent complex engineering problems due to the interaction between fire development, smoke movement, building geometry, ventilation, façade systems, structural response, and fire protection measures. The increased height of buildings limits the effectiveness of external firefighting and creates conditions for vertical smoke and fire spread through stairwells, elevator shafts, ventilation systems, and façade cavities. This paper reviews the principal fire safety and engineering aspects of high-rise building fires, with emphasis on fire dynamics, smoke and heat transport, internal and external fire spread, passive and active protection systems, evacuation and firefighting conditions, and engineering approaches to fire risk assessment. Particular attention is given to computational fluid dynamics (CFD), Fire Dynamics Simulator (FDS), travelling-fire scenarios, and performance-based fire safety engineering. The reviewed literature indicates that conventional prescriptive approaches may be insufficient for complex high-rise configurations and that reliable fire safety assessment requires an integrated consideration of realistic fire scenarios, smoke movement, protection systems, structural response, and firefighting conditions.
Key words: high-rise buildings; fire dynamics; smoke movement; fire spread; fire safety engineering; evacuation; CFD

INTRODUCTION

The rapid development of urban areas has resulted in an increasing number of high-rise buildings with complex structural, architectural, and mechanical systems. Although high-rise construction provides an efficient response to limited urban space, the vertical configuration of such buildings introduces specific challenges for fire safety. Building height, compartmentation, vertical shafts, façade systems, ventilation networks, and limited accessibility for external firefighting can significantly influence fire development and its consequences.

High-rise fires differ from fires in low-rise buildings because the vertical dimension creates long travel paths for smoke and hot gases and increases the importance of buoyancy-driven flow. Stairwells, elevator shafts, service ducts, and other vertical openings may provide pathways for rapid smoke transport, while façade systems may facilitate external vertical fire spread. Previous research has identified façade flame and plume behaviour, flame spread over façade materials, and buoyancy-driven smoke transport through long vertical channels as key aspects of high-rise fire dynamics (Alianto et al., 2022). The stack effect can further intensify vertical smoke movement as building height increases (Cho et al., 2025).

The engineering assessment of high-rise fires therefore requires consideration of several mutually dependent phenomena. Fire development determines the heat release rate and thermal environment, while ventilation, wind, and building geometry influence fire growth and smoke movement. The resulting thermal and smoke exposure affects occupants, firefighters, and structural elements, whereas the performance of compartmentation, detection, suppression, and smoke-control systems determines the extent to which fire development can be controlled.

The present review was based on relevant peer-reviewed and technical literature addressing high-rise fire dynamics, fire spread, smoke movement, fire protection, structural fire engineering, evacuation, and risk assessment. Particular attention was given to studies

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involving numerical modelling, experimental observations, realistic fire scenarios, and performance-based engineering approaches.
The objective of this paper is to provide an engineering-oriented review of fire safety in high-rise buildings, focusing on fire development and spread, protection systems, evacuation and firefighting conditions, and engineering methods for fire risk assessment.

FIRE DEVELOPMENT AND FIRE SPREAD IN HIGH-RISE BUILDINGS

Ecological aspects

Fire development is primarily determined by the available combustible materials, their distribution, ventilation conditions, and characteristics of the enclosure. Fire load is therefore one of the fundamental parameters influencing the potential heat release and duration of burning. A study of 50 high-rise residential buildings in Istanbul demonstrated considerable variation in fire-load density between different rooms and used FDS simulations to estimate fire growth and spread times. The study reported compartment peak heat release rates in the range of approximately 8–25 MW and fire spread times of approximately 1–11 min, depending on the compartment configuration (Dai et al., 2017).
The heat release rate (HRR) is particularly important because it determines the intensity of the thermal environment and strongly influences buoyant flow and smoke production. In high-rise buildings, these effects can be amplified by vertical communication paths and building-induced airflow.
Recent numerical research has also demonstrated that fire development can vary considerably depending on the position of a fire within a high-rise building and on the configuration of windows and doors. (Vovk et al., 2025) investigated a residential apartment on the 20th floor of a 22-storey building using FDS and found that openings and external wind affected fire development, airflow, the distribution of hazardous fire factors, and fire-detector response (Dundar & Selamet, 2023). These results demonstrate that fire development cannot always be adequately represented by a single simplified fire scenario.

Smoke movement and stack effect

Smoke movement is one of the most critical aspects of high-rise fire safety. Hot gases generated by a fire rise due to buoyancy and may rapidly enter vertical shafts and communication spaces. Stairwells, elevator shafts, ventilation ducts, and service shafts can therefore become important pathways for smoke propagation.
A field experiment conducted in the basement of a high-rise building demonstrated rapid vertical smoke transport through a stairwell. For a 0.125 MW fire scenario, smoke reached areas associated with the fourth or fifth floor within approximately 300 s, while the smoke-layer height at the stairwell corner decreased to approximately 2.0 m (Escrig et al., 2026). Such observations demonstrate the importance of considering actual vertical flow paths when evaluating smoke-control strategies.
The stack effect further contributes to smoke propagation. The pressure difference between the interior and exterior of a tall building is influenced by building height and temperature differences. During a fire, buoyancy-driven flow can increase vertical air movement and accelerate smoke transport. Cho and coauthors (2025) investigated a 49-storey residential building using CFD and System Dynamics and reported that the stack effect associated with building height can accelerate smoke propagation and increase risks during firefighting and rescue operations.
External wind represents an additional source of uncertainty. Recent research using CFD-generated wind-field data demonstrated that high-rise fire scenarios can involve complex airflow patterns, including changes in wind speed, direction, and vertical velocity (Fischer et al., 2022). Consequently, wind and fire-induced buoyancy should be considered as interacting phenomena when assessing high-rise fire behaviour.

The principal engineering factors affecting fire development and fire spread are summarized in Table 1.

Table 1. *Principal engineering factors affecting high-rise building fire development and spread*

Factor	Engineering effect	Values
Fire load	Determines potential heat release and fire duration	Increased fire severity
Ventilation	Controls oxygen supply and fire growth	Changes HRR and smoke production
Building height	Increases vertical pressure differences	Enhanced smoke movement
Vertical shafts	Provide low-resistance flow paths	Rapid vertical smoke spread
External wind	Modifies airflow and flame trajectory	Increased uncertainty in fire spread
Façade configuration	May provide vertical fire pathways	External fire spread
Compartmentation	Limits fire and smoke propagation	Reduced fire spread
Structural system	Determines response to thermal exposure	Loss of load-bearing capacity

Internal and external fire spread

Fire spread within high-rise buildings can occur horizontally between adjacent compartments and vertically through openings, shafts, façades, and other building elements. Effective compartmentation is therefore a fundamental passive fire protection measure.
External fire spread represents an additional risk because flames emerging from windows can impinge on façades and subsequently spread towards upper floors. This problem becomes particularly significant when combustible façade materials or inadequately protected cavities are present.
A recent review of existing high-rise residential buildings with combustible façades emphasized that façade systems, construction details, cavity barriers, joints, and seams must be considered when evaluating the potential for vertical external fire spread (Li et al., 2018). The authors also highlighted limitations of conventional façade fire testing in representing complex real-world fire scenarios.
The interaction between internal fire, façade geometry, cavity configuration, and external wind makes predicting façade fire spread particularly difficult. Therefore, façade fire safety should be considered as an integral component of the overall building fire safety strategy.

Internal and external fire spread

An additional engineering issue concerns the applicability of conventional design fire curves to large high-rise compartments. Traditional structural fire design commonly assumes relatively uniform burning and homogeneous temperature conditions within a compartment. However, research on large compartments indicates that fire may remain localized and move across a floor plate as combustible materials are consumed (Rein et al., 2007).
This phenomenon, known as a travelling fire, can produce substantially different thermal exposure than a uniform compartment fire. Rein et al. proposed an engineering methodology for defining realistic fire environments in complex multi-storey buildings, demonstrating the potential importance of non-uniform fire development for structural engineering (Ronchi & Nilsson, 2013).
Subsequent research has emphasized both the potential value and the limitations of travelling-fire models. Paper (Dai et al., 2017). identified the lack of sufficiently detailed large-scale experimental data as an important limitation for further development and validation of such models (Stern-Gottfried & Rein, 2012). Nevertheless, travelling-fire scenarios provide

an important basis for performance-based structural fire assessment in large open-plan compartments.

FIRE SAFETY AND ENGINEERING PROTECTION MEASURES

High-rise fire safety depends on the combined performance of passive and active protection systems. Because no individual measure can reliably control every possible fire scenario, these systems should be designed as complementary components of an integrated fire safety strategy.

Passive fire protection

Passive fire protection aims to limit fire development and propagation without requiring active intervention. Principal measures include fire-resistant structural elements, compartmentation, fire-rated walls and floors, fire doors, and fire stopping of service penetrations.
Compartmentation is particularly important because it limits horizontal and vertical fire spread and helps maintain protected circulation and escape routes. The effectiveness of compartmentation depends not only on the nominal fire resistance of individual elements but also on the continuity and integrity of the overall barrier system.
Façade protection should similarly be considered as part of passive fire safety. Appropriate material classification, cavity barriers, fire-resistant construction details, and control of joints and penetrations can reduce the probability of rapid external fire spread (Li et al., 2018).

Active fire protection

Active systems include automatic detection, alarm systems, sprinklers, and other suppression technologies. Early detection is particularly important in high-rise buildings because the vertical distance and complexity of evacuation and firefighting operations can increase response times.
The FDS investigation by Vovk and coauthors (2025) demonstrated that detector performance can be influenced by airflow and external wind conditions. In the investigated scenarios, wind and openings modified the airflow field and affected detector response (Dundar & Selamet, 2023). This indicates that detector performance should be evaluated not only on the basis of nominal spacing but also with consideration of airflow conditions where these are critical to system performance.
Automatic sprinkler systems can limit fire growth and heat release and consequently reduce the potential for fire spread. Their effectiveness, however, depends on appropriate design, maintenance, water supply, and compatibility with the fire scenario.

Smoke-control systems

Smoke-control systems are particularly important because smoke can propagate through vertical pathways considerably faster than the fire itself. Mechanical smoke extraction, stairwell pressurization, and protected elevator lobbies are among the principal engineering measures used to control smoke movement.
Alianto and coauthors (2022) reviewed 163 publications on smoke management in high-rise buildings. They emphasized the importance of smoke movement through elevator shafts, ventilation shafts, and stairwells, as well as the application of pressurization and extraction systems (Sun et al., 2013). Their review also supports performance-based approaches when prescriptive requirements cannot adequately describe actual building and fire conditions.
The effectiveness of smoke-control systems depends on building geometry, pressure differences, leakage characteristics, shaft configuration, and the interaction between natural and mechanical airflow. Consequently, smoke-control systems for complex high-rise buildings should preferably be evaluated under representative fire and environmental scenarios.

Figure 1 illustrates the principal sequence from fire ignition and growth to smoke movement, vertical and façade fire spread, and structural exposure. The schematic emphasizes the coupled nature of the physical processes rather than representing a single specific fire scenario.

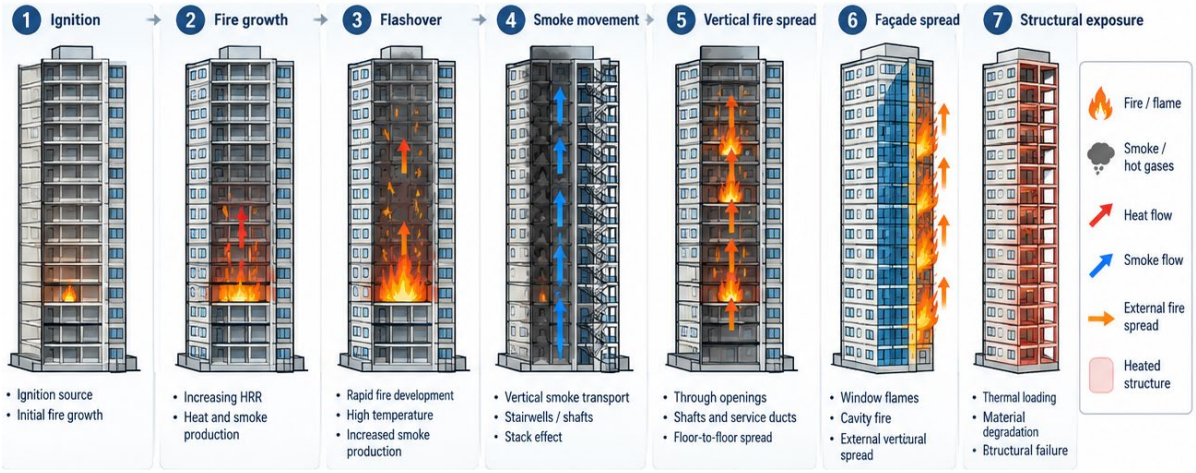


Fig. 1. *Schematic representation of fire development and fire spread mechanisms in a high-rise building.*

EVACUATION, FIREFIGHTING AND HUMAN SAFETY

Although the main focus of this review is engineering, evacuation and firefighting cannot be separated from the physical development of a high-rise fire. The available time for safe evacuation is directly influenced by smoke movement, temperature, toxic gases, and the performance of fire protection systems.

The concept of Available Safe Egress Time (ASET) provides an engineering framework for comparing the time before untenable conditions develop with the Required Safe Egress Time (RSET). In high-rise buildings, smoke propagation through stairwells and other vertical pathways can substantially reduce available evacuation time. Evacuation modelling research has demonstrated that high-rise evacuation is influenced by the configuration of stairs and elevators, occupant distribution, building use, and evacuation strategies (Vovk et al., 2025).

Firefighting operations are similarly constrained by the physical characteristics of high-rise buildings. Cho and colleagues (2025) discussed the limited operational reach of aerial ladder equipment and the need for firefighters to enter buildings through protected internal routes when fires occur above the practical reach of external equipment.

The same study linked CFD-based smoke propagation with a System Dynamics model to examine how smoke spread interacts with firefighting and evacuation operations (Cho et al., 2025). This type of coupled modelling illustrates the potential benefit of integrating physical fire phenomena with operational risk assessment.

FIRE RISK ASSESSMENT AND ENGINEERING ANALYSIS

The complexity of high-rise fires makes engineering analysis an essential component of both new building design and assessment of existing buildings. Risk assessment should consider not only the probability of fire initiation but also the consequences associated with different fire-development and fire-spread scenarios.

A basic risk formulation can be expressed as:

$$R = P \times C \tag{1}$$

where (R) is the risk, (P) is the probability of occurrence, and (C) represents the potential consequence. Although simple qualitative and semi-quantitative approaches are useful for

screening and prioritization, complex high-rise buildings increasingly require more advanced engineering methods.

CFD and FDS-based analysis

Computational Fluid Dynamics (CFD), including FDS, enables detailed investigation of fire-induced flow, temperature, smoke concentration, and pressure fields. The reviewed studies demonstrate applications of CFD to smoke movement, stack effect, detector response, wind–fire interactions, and firefighting risk (Cho et al., 2025; Dundar & Selamet, 2023; Fischer et al., 2022). The principal advantage of CFD is its ability to resolve spatially distributed physical phenomena that are difficult to represent using simplified calculations.
The study by Fischer and co-authors (2022) also demonstrates the possibility of combining CFD-generated data with machine-learning methods to obtain faster predictions of complex wind fields. Such approaches may become useful for repeated engineering analyses, although they should currently be regarded as complementary to physically based simulation.

Structural fire engineering

Structural response represents another important component of high-rise fire safety. Elevated temperatures can reduce the strength and stiffness of structural materials, cause thermal expansion and deformation, and potentially contribute to local or progressive structural failure.
For steel structures, the spatial and temporal distribution of fire exposure is particularly important. Research on travelling fires has shown that localized and moving fire scenarios can generate thermal exposures substantially different from those predicted by uniform standard-fire assumptions (Rein et al., 2007; Stern-Gottfried & Rein, 2012; Wu et al., 2025).
Fischer et al. demonstrated the relevance of travelling-fire modelling for performance-based structural fire engineering of steel-frame buildings, highlighting the importance of realistic fire scenarios where uniform fire assumptions may be inappropriate (Wu et al., 2025).

Performance-based fire safety engineering

Performance-based fire safety engineering provides a framework for integrating fire dynamics, smoke movement, evacuation, protection systems, and structural response. Instead of relying exclusively on prescriptive requirements, performance-based approaches evaluate whether defined safety objectives are achieved under specified fire scenarios.
Li and coauthors (2018) identified performance-based design as an important direction in modern fire safety engineering for high-rise buildings and emphasized the importance of defining fire scenarios, performance objectives, and appropriate engineering criteria.

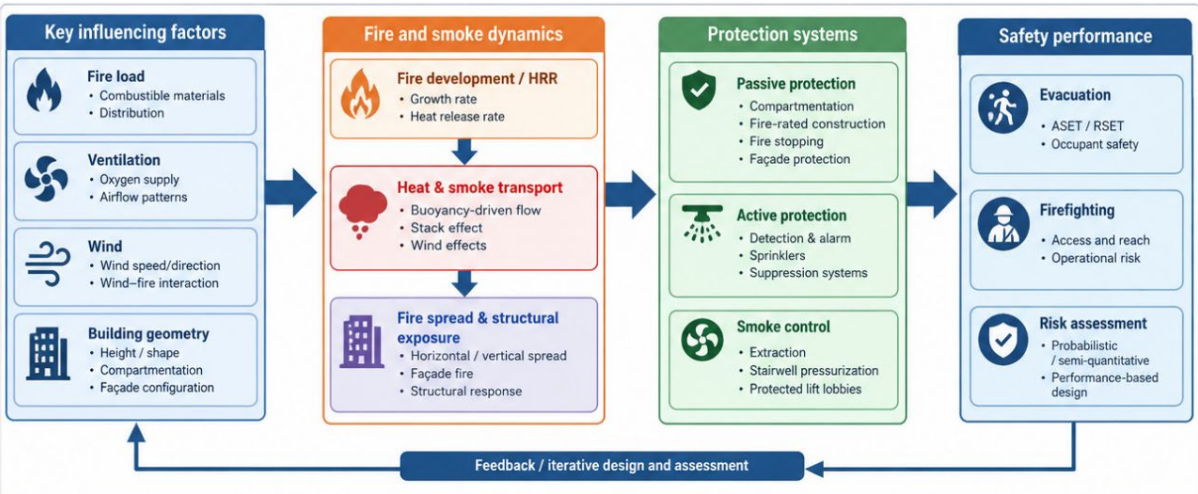


Fig. 2. *Schematic representation of fire development and fire spread mechanisms in a high-rise building.*

Figure 2 provides an overview of the engineering interactions among fire load, ventilation, wind, and building geometry, as well as fire development and heat release, smoke and heat transport, fire spread and structural exposure, and passive and active fire protection measures.

DISCUSSION

The reviewed literature demonstrates that fire safety in high-rise buildings is a coupled engineering problem in which fire development, smoke movement, fire spread, protection systems, structural response, evacuation, and firefighting are strongly interconnected.

Several dominant engineering factors can be identified. First, fire development is strongly influenced by fire load, ventilation, openings, and compartment characteristics. Second, vertical shafts and the stack effect can substantially accelerate smoke propagation. Third, façade systems may provide an important pathway for vertical external fire spread, particularly when combustible materials or inadequately protected cavities are present. Fourth, conventional uniform fire scenarios may not adequately represent all realistic high-rise fires, particularly in large open-plan compartments where travelling fires may develop.

The performance of passive and active protection systems is therefore critical. Compartmentation, fire-resistant construction, detection, sprinklers, and smoke-control systems should be considered as interacting components of a common fire safety strategy. Their performance may also depend on wind, ventilation, building geometry, and the specific fire scenario.

Modern computational methods provide increasingly powerful tools for high-rise fire assessment. CFD and FDS can be used to investigate fire development, smoke movement, airflow, and wind–fire interactions, while structural fire models can evaluate the thermal and mechanical response of load-bearing systems. Risk-based and performance-based approaches can then integrate these results into an overall assessment.

Nevertheless, important limitations remain. Advanced models depend on assumptions concerning fire growth, ventilation, material properties, and boundary conditions, while experimental data for realistic large-scale high-rise fire scenarios remain limited. Further research should therefore focus on validation of coupled fire–smoke–structure models, realistic façade-fire scenarios, travelling fires, wind effects, and integrated performance-based assessment of existing high-rise buildings.

CONCLUSIONS

High-rise building fire safety cannot be reliably addressed by considering individual protection measures in isolation. The reviewed studies indicate that fire development, smoke

and heat transport, internal and external fire spread, structural response, evacuation, and firefighting are closely interconnected and should therefore be considered within an integrated engineering framework.

The assessment of high-rise fire safety should combine realistic fire scenarios with appropriate passive and active protection measures, smoke-control analysis, structural fire engineering, evacuation assessment, and risk-based evaluation. Advanced computational approaches, including CFD/FDS and performance-based fire safety engineering, provide valuable tools for analysing these interactions and supporting engineering decisions.

At the same time, the reliability of such assessments depends on the quality of input assumptions, model validation, and the availability of realistic experimental data. Future research should therefore emphasize validation of coupled fire–smoke–structure models, realistic façade-fire and travelling-fire scenarios, wind effects, and integrated assessment of existing high-rise buildings.

Overall, an integrated engineering approach combining realistic fire scenarios, smoke and heat transport analysis, passive and active protection, structural fire engineering, and risk assessment provides a more reliable basis for high-rise fire safety design and evaluation.

ACKNOWLEDGEMENT

This work has been supported by the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia, through the Contract for the scientific research financing in 2026, 451-03- 34/2026-03/200108 to build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation, which is the ninth goal of the UN's 2030 Agenda for Sustainable Development.

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