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An Analytical Study Of Fire Spread Mechanisms In High-Rise Buildings Considering Facade Materials

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Abstract
Fire spread in high-rise buildings has become a major global safety concern due to the increasing use of combustible façade systems, insulation materials, and modern architectural cladding. Recent catastrophic incidents such as the demonstrated how combustible façade materials can accelerate vertical and horizontal fire spread, leading to extensive property damage and significant loss of life. This study analytically investigates fire spread mechanisms in high-rise buildings with special emphasis on façade materials, insulation systems, cavity configurations, and ventilation effects. The research evaluates combustible and non-combustible façade systems using available experimental data, numerical investigations, and international fire safety standards. Results indicate that polyethylene-filled aluminum composite material (ACM) panels exhibit peak heat release rates approximately 55 times greater than non-combustible alternatives, while polyisocyanurate insulation generates smoke toxicity nearly 15 times higher than mineral wool insulation. The study concludes that façade combustibility, chimney effects in ventilated cavities, and inadequate fire barriers significantly contribute to rapid fire propagation. Recommendations are proposed in accordance with NBC 2016, NFPA 285, and BS 8414 standards for improved fire-safe façade design in high-rise structures.

Keywords: High-rise buildings, façade materials, fire spread, ACM cladding, insulation, fire dynamics, smoke propagation, CFD modeling, façade fire safety.

1. Introduction

Rapid urbanization and vertical development have increased the construction of high-rise buildings worldwide. Modern high-rise structures commonly utilize lightweight façade systems for thermal insulation, energy efficiency, and aesthetic enhancement. However, several façade materials possess combustible characteristics that can intensify external fire spread.

The in London caused 72 fatalities and exposed severe deficiencies in combustible façade systems. Investigations revealed that aluminum composite panels with polyethylene cores and combustible insulation significantly accelerated flame spread across the building exterior.

High-rise façade fires present unique challenges because flames can propagate vertically through:

- External cladding systems
- Ventilated façade cavities
- Window-to-window flame leap
- Combustible insulation layers
- Thermal radiation effects
- Wind-assisted flame spread

The increasing use of façade cladding in modern buildings necessitates detailed analytical studies to understand fire spread mechanisms and establish effective fire protection measures.

2. Objectives of the Study

The primary objectives of this research are:

1. To analyze fire spread mechanisms in high-rise buildings.
2. To evaluate the influence of façade materials on fire propagation.
3. To compare combustible and non-combustible façade systems.
4. To assess smoke toxicity and thermal release characteristics.
5. To examine international façade fire safety standards.
6. To recommend mitigation strategies for safer high-rise construction.

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3. Literature Review
Several researchers have investigated façade fire behavior after major high-rise fire incidents.
A study published in the *Journal of Hazardous Materials* reported that polyethylene-based ACM panels exhibited:
- 55 times greater peak heat release rate (pHRR)
- 70 times greater total heat release (THR)

compared to non-combustible façade panels.
The same study found:
- Polyisocyanurate (PIR) insulation showed 16 times higher pHRR
- Phenolic foam produced 48 times greater THR than mineral wool insulation
- PIR smoke toxicity was approximately 15 times higher than mineral wool insulation.

Research on façade cavity behavior demonstrated that ventilated air gaps create a "chimney effect," accelerating upward flame propagation due to buoyancy-driven airflow. Large-scale BS 8414 façade tests confirmed that flames can spread several floors within minutes under cavity ventilation conditions.
Studies further revealed that improper installation of cavity barriers and combustible insulation contributes significantly to vertical flame spread in high-rise façades.

4. Fire Spread Mechanisms in High-Rise Buildings
4.1 Compartment Fire Spill Plume
The initial stage of façade fire spread usually begins with an internal compartment fire. Once windows fail due to thermal stress, flames eject outward and rise along the building façade.
The external flame height can exceed:
- 2–3 m above the window opening
- Temperatures may reach 700–900°C near the façade surface.

These flames ignite combustible cladding materials installed above the fire floor.

4.2 Vertical Flame Spread
Vertical spread occurs primarily due to:
- Thermal buoyancy
- Convective heat transfer
- Radiative heating

Combustible façade systems allow flames to rapidly climb upward. Wind conditions further intensify vertical spread.
The Grenfell Tower fire spread across all four elevations within a few hours due to combustible ACM cladding and insulation systems.

4.3 Chimney Effect in Ventilated Cavities
Ventilated façade systems contain air cavities between cladding and insulation layers. During fire exposure:
- Hot gases rise rapidly through cavities
- Oxygen supply increases combustion intensity
- Fire spreads vertically through concealed spaces

This mechanism acts similarly to a chimney, significantly accelerating flame spread.
Experimental BS 8414 tests used façade rigs approximately:
- 8 m high
- 2.6 m wide

to simulate real façade fire behavior.
4.4 Melting and Dripping of Thermoplastics
Polyethylene cores within ACM panels melt during fire exposure and produce flaming droplets.
Research identified a "novel fire growth mechanism" where molten polyethylene drips ignite insulation foam, causing rapid façade ignition.
4.5 Window Leapfrog Effect
Flames emerging from lower floors can re-enter upper floors through broken windows. This phenomenon:
- Causes multi-floor involvement
- Compromises evacuation routes
- Accelerates flashover conditions

Wind speed and façade geometry strongly influence leapfrog fire spread.

5. Types of Facade Materials and Their Fire Performance

Facade Material	Combustibility	Fire Performance	Typical Application
Aluminum Composite Material (PE Core)	Highly combustible	Rapid flame spread	Commercial towers

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Facade Material	Combustibility	Fire Performance	Typical Application
Fire-Retardant ACM	Moderate	Improved resistance	Mixed-use buildings
Mineral Wool Panels	Non-combustible	Excellent fire resistance	High-rise insulation
High Pressure Laminate (HPL)	Combustible	High heat release	Decorative façades
Glass Curtain Walls	Low combustibility	Vulnerable to thermal breakage	Office towers
Fiber Cement Boards	Non-combustible	Good fire performance	Residential towers

6. Comparative Analysis of Facade Materials

Parameter	PE ACM Panels	HPL Panels	Mineral Wool System
Peak Heat Release Rate	55× higher	25× higher	Very low
Total Heat Release	70× higher	115× higher	Minimal
Smoke Toxicity	High	Moderate	Very low
Flame Spread Rate	Rapid	Moderate	Negligible
Fire Classification	Combustible	Combustible	Non-combustible

Data adapted from façade combustion studies.

7. Smoke Propagation and Toxicity
Smoke inhalation remains the primary cause of fatalities during high-rise fires.
Combustible façade materials generate:
- Carbon monoxide (CO)
- Hydrogen cyanide (HCN)
- Dense black smoke

Studies reported that:
- 1 kg of burning PIR insulation can fill a 50 m^3 room with incapacitating toxic gases.

Smoke migration occurs through:
- Stairwells
- Elevator shafts
- HVAC ducts
- Façade cavities

Inadequate smoke control systems increase occupant vulnerability.
8. Fire Modeling and Simulation Approaches
8.1 Computational Fluid Dynamics (CFD)
CFD models are widely used for façade fire simulations. Common software includes:
- Fire Dynamics Simulator (FDS)
- PyroSim
- ANSYS Fluent

CFD models evaluate:
- Flame spread velocity
- Smoke movement
- Thermal radiation
- Wind influence

8.2 Zone Modeling
Zone models divide buildings into compartments and predict:
- Smoke layer formation
- Temperature distribution
- Tenability conditions

8.3 Large-Scale Fire Testing
Major façade fire standards include:

Standard	Country	Purpose
BS 8414	UK	Façade fire testing
NFPA 285	USA	Exterior wall assembly testing
NBC 2016	India	Fire and life safety
ISO 13785	International	Façade fire performance

9. Discussion

The analytical findings demonstrate that façade materials critically influence fire behavior in high-rise buildings.
Key observations include:

- Combustible ACM systems drastically increase heat release rates.
- Ventilated cavities intensify upward flame propagation.
- Thermoplastic materials contribute to secondary ignition.
- Inadequate cavity barriers permit concealed fire spread.
- Smoke toxicity from foam insulation significantly increases casualty risks.

The study confirms that non-combustible façade systems such as mineral wool insulation and fiber cement panels provide substantially improved fire performance.

10. Recommendations

The following measures are recommended for high-rise façade fire safety:

1. Ban polyethylene-core ACM panels in high-rise buildings.
2. Use non-combustible insulation materials such as mineral wool.
3. Install effective cavity barriers at every floor level.
4. Conduct mandatory large-scale façade fire tests.
5. Implement real-time fire detection systems.
6. Ensure compliance with NBC 2016 and NFPA 285.
7. Improve evacuation planning and smoke control systems.
8. Utilize CFD-based fire risk assessment during design stages.

11. Conclusion

This study analytically evaluated fire spread mechanisms in high-rise buildings considering façade materials and associated fire dynamics. The findings demonstrate that combustible façade systems significantly increase fire intensity, smoke toxicity, and vertical flame spread rates.

Major façade fire disasters have revealed that polyethylene-core ACM panels, combustible insulation, and poorly designed ventilated cavities are primary contributors to rapid external fire propagation. Non-combustible façade materials and strict regulatory compliance remain essential for improving high-rise fire safety.

Future research should focus on:

- AI-based fire prediction systems
- Digital twin fire monitoring
- Smart façade technologies
- Advanced CFD fire simulations

The study emphasizes the urgent need for stricter façade fire regulations and safer construction practices in modern urban environments.

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