Civil Engineering and Architecture 13(3): 2036-2065, 2025 http://www.hrpub.org
DOI: 10.13189/cea.2025.130342

Fire Safety Challenges in Electrical Shafts: A Case of Fire Accident at High Rise Residential Building in Bengaluru, India

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Received January 8, 2025; Revised March 28, 2025; Accepted April 21, 2025

Cite This Paper in the Following Citation Styles

(a): *[1] Mamatha N., Ajai Chandran C. K. , "Fire Safety Challenges in Electrical Shafts: A Case of Fire Accident at High Rise Residential Building in Bengaluru, India," Civil Engineering and Architecture, Vol. 13, No. 3, pp. 2036 - 2065, 2025. DOI: 10.13189/cea.2025.130342.*

(b): *Mamatha N., Ajai Chandran C. K. (2025). Fire Safety Challenges in Electrical Shafts: A Case of Fire Accident at High Rise Residential Building in Bengaluru, India. Civil Engineering and Architecture, 13(3), 2036 - 2065. DOI: 10.13189/cea.2025.130342.*

Abstract Fire safety in high-rise residential buildings is a complex issue, especially when it comes to electrical shaft fires. These enclosed vertical shafts help the rapid spread of smoke, toxic gases and heat across different floors and pose a high risk to the occupants and affect the evacuation process. However, the actual life fire outbreaks show that the existing measures are still wanting as far as evacuation safety is concerned. These issues are addressed in this research through the use of performance-based fire design (PBFD) to assess fire behaviour and evacuation patterns in high-rise buildings. The study then simulates using PyroSim and Pathfinder simulation software, the visibility of smoke, reduction of visibility, CO and CO_2 levels, temperature changes, and congestion of the evacuation corridors. Unlike other studies, this paper combines both fire development and occupants' response to give a holistic approach to the issue of evacuation challenges. One of the findings of this research is the analysis of the ASET and RSET whereby it was found that the current provisions in fire safety do not ensure a safe exit. It was established that RSET is much higher than ASET, which points to a severe lack in current fire safety solutions. Simulations incorporating NBC-2016 (National Building Code-2016) provisions—such as fire-rated doors, sprinklers, and mechanical ventilation—demonstrate improved outcomes, reducing RSET from 1,272 seconds to 746 seconds. However, persistent challenges such as congestion, bottlenecks, and hazardous gas levels highlight the need for enhanced fire safety strategies. This research offers practical recommendations to improve evacuation effectiveness through better ventilation, compartmentalization, and advanced suppression systems. The findings contribute to risk mitigation strategies, expand the knowledge base for fire safety, and provide a foundation for improving fire safety regulations in high-rise buildings.

Keywords ASET, Evacuation, Fire Safety, High-Rise Buildings, NBC-2016, Performance-Based Design, RSET

1. Introduction

Residential fire safety in high-rise buildings is a major concern due to their multi-story structures, complex layouts, high occupancy levels, and vertical design [1],[2]. Fires originating in enclosed areas such as electrical shafts are particularly hazardous, as these shafts facilitate the rapid spread of smoke and heat across multiple floors. This leads to low visibility, build up of toxic gases, and hot temperatures, making it difficult to evacuate and posing great dangers to the occupants and fire fighters [3],[4]. These issues call for the implementation of PBFD, which is a better approach than prescriptive codes and offers customised, research-backed fire protection measures [5],[6].

PyroSim and Pathfinder are two computer-based simulation programmes used at PBFD to predict the behaviour of fire and the movement of people in case of an evacuation. PyroSim tools are valuable in depicting fire behaviours such as the movement of smoke, its obscuration, temperature changes, and toxic gas dispersion. It stresses how much conditions before the fire, especially in the first moments of fire, affect the evacuation process. It has been found that factors like whether a door is fire-rated or open have an impact on the level of smoke and heat spread and, hence, the evacuation outcome [7]. Electrical shaft fires produce a significant amount of smoke, and the visibility is affected as well as the CO levels rise quickly [8]. In the case of electric shaft fires, visibility is quickly compromised, and the CO level rises, hence the need for smoke control and pressurised stairwells.

Pathfinder integrates with PyroSim to model human behavior during evacuation, considering factors such as occupant density, movement speed, and decision-making in emergency scenarios. It facilitates the understanding of crowd flow characteristics, congestion areas, and evacuation delays caused by low visibility and bottlenecks [9]. Together, these tools provide a systematic approach to studying the interaction between fire conditions and human actions during high-rise building fires.

This paper aims to evaluate the performance of electrical shaft fires in high-rise residential buildings under normal functioning conditions. It evaluates the extent, to which NBC-2016 safety measures—such as fire doors, sprinklers, and mechanical ventilation—enhance evacuation outcomes. However, persistent issues such as congestion and unsafe gas levels remain, highlighting the need for improved evacuation strategies. Fire safety in high-rise residential buildings, particularly in small compartments such as electrical shafts, has become a focal area in fire safety engineering. Current research indicates difficulties in managing fire behavior and evacuation effectiveness, driving a shift towards PBFD and high-fidelity simulation tools.

Electrical shafts serve as vertical conduits for electrical wiring but also act as pathways for smoke, heat, and toxic gases during fires. The door state plays a crucial role in determining the extent of smoke and heat propagation [7]. Fires that occur in electrical shafts are dangerous as they are capable of spreading to other floors and blocking the evacuation paths. Research on cable fires has shown that there are higher concentrations of carbon monoxide (CO) and carbon dioxide (CO_2) in addition to faster-growing smoke that causes low visibility and slows down the process of evacuation [8].

PyroSim is widely used to predict the spread of smoke, visibility reduction, temperature variations, and toxic gas concentrations. Research indicates that the nature of fire growth within the first 60 seconds is crucial in determining evacuation success. Pressurized staircases and smoke control mechanisms are critical factors in maintaining safe escape corridors during high-rise building fires [9].

Occupant behavior significantly influences the effectiveness of an evacuation. Pathfinder simulations model crowd movements, taking into account factors such as walking speed, occupant density, and decision-making processes. Congestion and bottlenecks are common issues that slow down evacuation. Lack of visibility and exposure to toxic gases also affects evacuation behaviour, which underlines the importance of proper design of evacuation routes [10].

ASET and RSET are the two primary measures used in fire safety risk evaluation. Despite the fact that the goal of most research is to reduce RSET by enhancing fire detection and escape route identification, there is little literature on how such aspects apply to electrical shaft fires. Maintaining the RSET below ASET is important in high-rise buildings where evacuation is always a challenge [11].

The NBC-2016 contains provisions for fire safety features like fire doors, sprinklers, mechanical ventilation, etc. Although these provisions assist in managing the risks, their use in electrical shafts has not been implemented fully. It has been found that the use of mechanical ventilation is not enough to prevent smoke from penetrating through the vertical openings [12].

Electrical shaft fires are challenging to manage due to their enclosed environment, rapid production of smoke, and the possibility of compromising the integrity of the vertical shafts. It is seen that there is a pressing need to enhance the ventilation systems, segregation, and the advanced fire fighting techniques. That is why it is critical to fill the above-stated gaps to improve fire safety in high-rise residential buildings. The current study employs both PyroSim and Pathfinder in a combined manner to comprehensively investigate electrical shaft fires and offer novel findings regarding the fire behaviour, evacuation, and NBC-2016 provisions in high-rise residential buildings.

This paper can be used to build upon the research on the effectiveness of fire safety measures in enclosed vertical structures, such as the use of PBFDs and high-fidelity fire and evacuation simulations.

The following hypotheses guide the research:

1. Fires originating from electrical shafts significantly delay evacuation due to rapid smoke spread and gas accumulation.
2. The Required Safe Egress Time (RSET) for high-rise residential buildings is more than the Available Safe Egress Time (ASET) under the existing fire safety provisions.
3. Implementing NBC-2016 recommendations reduces RSET and improves evacuation efficiency.
4. Challenges such as congestion and unsafe gas concentrations persist even after applying NBC-2016 provisions.
5. Sophisticated fire alarms, better ventilation, and compartmentation are required to meet the fire safety requirements and to evacuate safely.

In achieving these objectives and hypotheses, this study shall seek to offer a detailed understanding of fire safety issues in high-rise buildings and come up with recommendations that enhance evacuation plans and occupant safety. The conclusions help to progress performance-based fire safety design and enhance the solutions for higher-risk situations.

1. Buildings with pressurized staircases showed significantly faster evacuation times
2. Modern safety systems (Brigade Gateway) resulted in zero fatalities
3. Detection time directly correlated with casualty numbers
4. Properties with recent safety upgrades showed better containment of fire spread

2. Real World Validation

The accidents occurred in the high rise residential buildings and its details are mentioned in Table 1.

Table 1. Consolidated Comparison of High-Rise Electrical Shaft Fire Incidents (2019-2023)

Parameter Category	Parameter	Hiranandani Heritage, Mumbai	Brigade Gateway, Bangalore	DLF Capital Greens, Delhi
Building Details	Location	Kandivali East, Mumbai	Malleswaram, Bangalore	Moti Nagar, Delhi
	Height	18 stories	22 stories	15 stories
	Construction Year	2008	2012	2015
	Number of Units	76 apartments	115 apartments	92 apartments
Incident Details	Date	December 12, 2019	March 15, 2021	January 8, 2023
	Time	19:45 IST	14:20 IST	23:15 IST
	Fire Origin	10th-11th floor shaft	8th-floor shaft	5th-6th floor shaft
	Cause	Main electrical wiring short circuit	Cable overheating	Cable insulation failure
Casualties	Fatalities	2 (elderly residents)	0	1 (maintenance worker)
	Injuries	14 (incl. 3 firefighters)	8 (minor)	11 (incl. 2 security)
	Smoke Inhalation Cases	23	17	19
Evacuation Details	Total Occupants	184	245	156
	Evacuation Time	42 minutes	38 minutes	35 minutes
	Primary Bottleneck	Main stairwell	Service elevator lobby	Ground floor exit
	Detection Time	4 minutes	2 minutes	3 minutes
	Smoke Spread Rate	2.1 floors/minute	1.8 floors/minute	1.9 floors/minute
	Peak CO Levels	310 ppm	280 ppm	295 ppm
Property Impact	Affected Floors	10th to 14th	8th to 12th	5th to 8th
	Structural Damage	Moderate	Minor	Minor
	Electrical Damage	Severe	Moderate	Severe
	Estimated Cost	₹2.8 crores	₹1.5 crores	₹1.9 crores
Safety Systems	Sprinkler System	Partially functional	Fully functional	Functional
	Fire Doors	Not installed	Partially installed	Recently installed
	Smoke Detection	Basic	Advanced	Advanced
	Emergency Lighting	Inadequate	Adequate	Adequate
	Pressurized Staircase	No	Yes	Partial
SOURCE [31],[32], [33] [13],[14], [15]		"Massive fire at Hiranandani Heritage Tower in Kandivali East, Mumbai." *Hindustan Times*, 12 Dec. 2019, https://www.hindustantimes.com/mumbai-news.	"Electrical shaft fire in Brigade Gateway, Bangalore." *Times of India*, 15 Mar. 2021,	"Fire at DLF Capital Greens: Cable insulation failure incident." *India Today*, 8 Jan. 2023,

Key Findings:

1. Buildings with pressurized staircases showed significantly faster evacuation times
2. Modern safety systems (Brigade Gateway) resulted in zero fatalities
3. Detection time directly correlated with casualty numbers
4. Properties with recent safety upgrades showed better containment of fire spread

3. Research Gap

Research on electrical shaft fires in high-rise buildings is limited, particularly in understanding how smoke, heat, and toxic gases spread through these vertical shafts, significantly impacting evacuation. These enclosed spaces act as conduits for rapid fire propagation, making evacuation more challenging and increasing risks for occupants and emergency responders. While PyroSim and Pathfinder simulations offer valuable insights into fire dynamics such as the smoke, CO (Carbon Monoxide), CO_2 (Carbon-di-Oxide), and Smoke Visibility, which are studied and cause the difficulty during evacuation Process and the Path Finder Simulations helps to analyse the people movement, congestion and bottle necks of the occupants during evacuation, their combined use to analyze electrical shaft fire scenarios remains underexplored.

Furthermore, the effectiveness of NBC-2016 provisions—such as fire-rated doors, sprinklers, and mechanical ventilation—has primarily been evaluated in isolation rather than as an integrated system. Their collective impact on reducing fire hazards, improving smoke control and visibility, and ensuring safe evacuation has not been comprehensively assessed. This study addresses these gaps by comparing ASET and RSET under both real-world conditions and enhanced safety measures, contributing to the advancement of PBFD in high-rise residential buildings.

4. Research Method

This study employs a **performance-based fire design (PBFD) approach** to analysing electrical shaft fire scenarios in high-rise residential buildings. The following are some of the steps involved in the methodology:

1. **Problem Identification and Research Scope**
   - The following paper aims to present a literature review of the various aspects of fire growth in enclosed vertical shafts.
   - These are the primary steps to identify the limitations in the existing fire safety provisions and evacuation plans.
2. **Simulation Tools and Data Collection**
   - Use **PyroSim** for simulating the fire growth, smoke movement, and temperature distribution.
   - Perform occupant evacuation behaviour analysis of fire scenarios using **Pathfinder**.
   - Incorporate real-world building layouts and occupancy data for accurate modeling.
3. **Scenario Development and NBC-2016 Provisions**
   - Develop baseline scenarios corresponding to the existing norms of fire safety.
   - The steps that have been taken in the current **NBC-2016 code** include fire-rated doors, sprinklers, and mechanical ventilation, and the effects of these provisions will be determined.
4. **ASET vs. RSET Analysis**
   - Determine the **Available Safe Egress Time (ASET)** by using fire and smoke spread models.
   - Calculate **Required Safe Egress Time (RSET)** with the help of evacuation modelling.
   - Compare **ASET** and **RSET** in order to determine the efficiency of the evacuation.
5. **Result Interpretation and Recommendations**
   - Some of the challenges that can be easily detected include congestion, bottlenecks, and high concentrations of gas.
   - Propose improvements in ventilation, compartmentalization, and suppression systems.

5. Modeling and Simulation Software

5.1. Introduction to PyroSim Software

PyroSim is a fire dynamics simulation software developed by Thunderhead Engineering based on the Fire Dynamics Simulator (FDS), which is a computational fluid dynamics model designed by the National Institute of Standards and Technology (NIST). PyroSim provides a user-friendly graphical interface that eliminates need for manual coding, allowing users to build, view, and simulate fire scenarios with greater accuracy and efficiency. It includes features for fire model creation, grid and fire source setup, combustion response characteristics, and result visualization. Also, it is compatible with Smokeview through which users can animate and analyze fire dynamics in an enhanced way. These features make PyroSim a versatile and accurate tool for studying fire behavior and its impact on building safety systems [16],[17].

5.2. Introduction to Pathfinder Software

Pathfinder is an evacuation simulation software that is based on agents and intended to simulate human behaviour during emergencies. It allows the visualization of evacuation characteristics such as crowd flow, path choice, and density for different motion groups and isolated pedestrians. Pathfinder also allows customization of personal attributes, such as walking speed, shoulder width, and height, to reflect realistic evacuation conditions. Its advanced features provide insights into critical aspects, such as congestion at emergency exits, evacuation flow density, and blockages, through both 2D and 3D animations. These capabilities make Pathfinder an essential tool for designing and optimizing evacuation strategies in complex environments [18].

6. Model Construction

This paper mainly selects an existing 15-story high-rise residential building located in a moderately developed area in Bangalore as a research object. Moreover, the selected building area is about 1150 sqm/floor and the overall height is 45m, of which the floor-to-floor height is 3m. The whole building is semicircular and has a central atrium and two cores, each core has an entry to 4 units on every floor. **Figure 1** shows the typical floor plan of the apartment.

Figure 1 illustrates the architectural plan of a typical high-rise residential apartment situated in a moderately developed area of Bangalore. The building design comprises a central atrium and two cores, each providing access to four residential units on every floor. The sole means of evacuation during a fire emergency is the Fire Escape Staircase (FES). However, several critical deficiencies were identified in the FES design. **Figure 2** illustrates the Architectural Revit model of the building, which is inturn imported to Pyrosim and Pathfinder for Simulations.

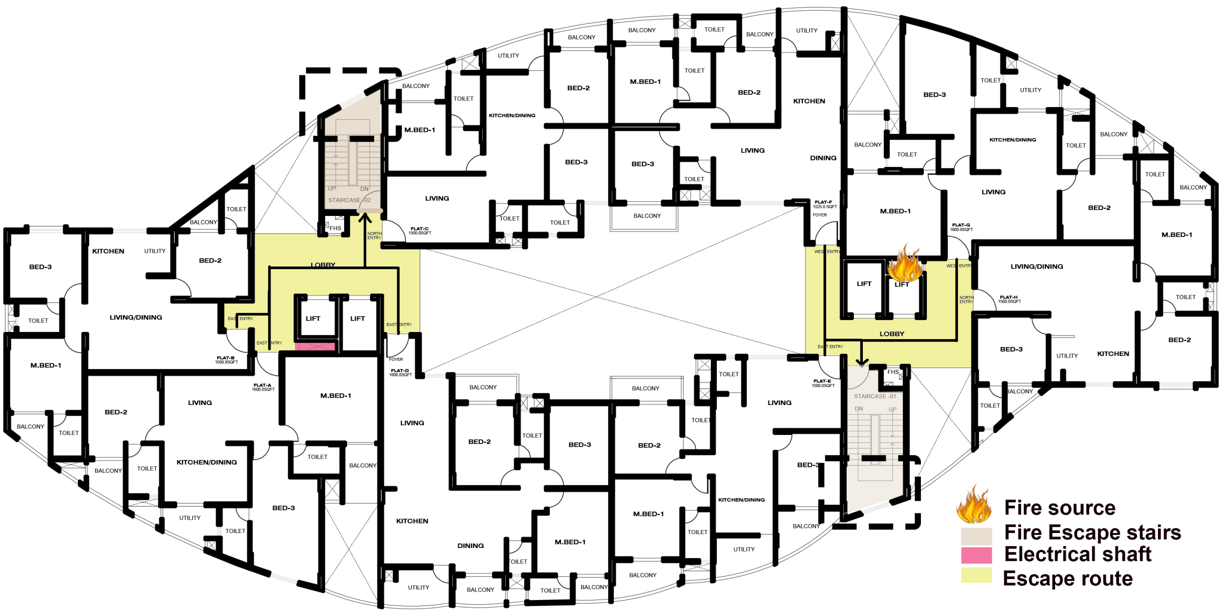


Figure 1. Typical floor plan of the apartment

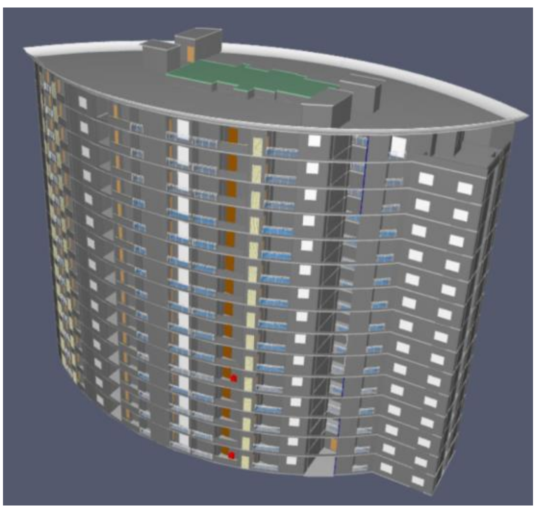


Figure 2. 3D model of the Building for simulation

The FES lacks essential safety provisions as stipulated by the National Building Code (NBC-2016). Notably, the staircase is not pressurized nor has cross ventilation, leading to potential ingress of smoke during a fire, which can hinder evacuation and pose significant risks to occupants. Also, the landing area is less than 1.2 meters, while the NBC-2016 standards for high-rise buildings require a minimum width of landing area. In addition, there is a lack of adequate and clear signs that indicate the evacuation corridors which makes it difficult for residents to identify safe routes to take during emergencies.

In this case, the fire source is placed inside electrical shaft which is a vertical shaft in the building. The fire starts on the fourth floor from an electrical short circuit and quickly spreads through the shaft as it is like a chimney which helps in spreading smoke and heat to various floors. This scenario underscores the importance of fire-rated enclosures, appropriate ventilation systems, and fire suppression systems within electrical shafts to avoid such risks [7],[8],[19]. These deficiencies make it necessary to follow the performance-based fire safety design and NBC-2016 recommendations to minimize such risks and protect the occupants. Table 2 is the checklist of the fire provisions according to NBC 2016.

During the electrical short circuit in a high rise residential building, the impact of the cable insulation and the details are discussed in Table 3 [20],[21],[22].

Table 2. Check list of Fire Evacuation provisions According to NBC 2016 and the Actuals per the site

Aspect	Details	Actuals as per the site
Escape Routes	- Maximum travel distance: - 22.5 m without sprinklers. - 30 m with sprinklers. - Minimum width: 1.2 m.	Yes
Fire Escape Staircase	- Mandatory for buildings taller than 15 m. - Minimum width: 1.2 m. - Must be cross-ventilated or pressurized to prevent smoke ingress if the Fire escape stairs have an internal staircase with an external wall. - Protected with fire-rated doors. - Must lead directly to ground level or a safe zone.	Cross ventilation is not provided, nor the staircase is pressurized, and the landing width is less.
Fire Exits	- Must lead directly to safe outdoor areas or refuge. - Minimum width: 1.0 m. - Marked with illuminated signage.	Signages missing
Refuge Areas	- Mandatory for buildings taller than 30 m. - Location: Every 4th floor or as required. - Minimum area: 15 m^2 or 0.3 m^2 per person.	Missing
Electrical Shaft Safety	- Enclosure: Shafts must be enclosed with 2-hour fire-rated walls and fire-rated doors. - Penetration Sealing: All cable penetrations must be sealed with fire-stopping materials to prevent fire and smoke spread. - Ventilation: Proper ventilation to prevent heat buildup. - Sprinklers: Install sprinklers or alternative fire suppression systems. - Accessibility: Ensure access panels are fire-rated and allow for periodic maintenance.	The doors are not sealed, no proper ventilation, and the sprinklers missing.
Ventilation and Smoke Management	- Natural or mechanical ventilation to reduce smoke. - Pressurization for staircases, lift shafts, and lobbies.	Missing
Emergency Equipment	- Fire alarms and detectors to cover all areas. - Sprinklers are mandatory for high-rise buildings. - Hydrants and hose reels on every floor. - Emergency lighting for escape routes and refuge areas.	Sprinklers missing, refuge is not provided
Compliance and Drills	- Adherence to NBC Part 4. - Conduct periodic evacuation drills for high-rise buildings.	Yes

Source: Bureau of Indian Standards (BIS), National Building Code of India (NBC-2016), Part 4: Fire and Life Safety, 2016 [19].

Table 3. Fire Safety Parameters and Impact of Cable Insulation in High-Rise Residential Building

Parameter	**Details**
Building Configuration	15 floors with cabling for 4 3BHK apartments per floor.
Cable Material	PVC or polyethylene insulation.
Cable Weight (Per Floor)	200–400 kg (for 4 apartments).
Total Cable Weight	3,000–6,000 kg (for 15 floors).
Combustible Surface Area	600–2,400 m^2(approx.).
HRR (PVC Cables)	400–800 kW/m^2
HRR (Polyethylene Cables)	500–1,000 kW/m^2
Fire Spread Dynamics	- Chimney effect accelerates fire spread. - Flashover conditions likely.
Fire-Rated Walls	Contain fire within the shaft but do not reduce HRR.
Ventilation Impact	Increase oxygen supply, potentially raising HRR to higher limits.
Evacuation Impact	High HRR produces intense heat and toxic smoke, reducing escape time.

Source: SFPE Handbook of Fire Protection Engineering, 5th ed., Society of Fire Protection Engineers, 2016 and ISO, "ISO 5660-1: Reaction-to-fire tests – Heat release, smoke production, and mass loss rate," 2020.

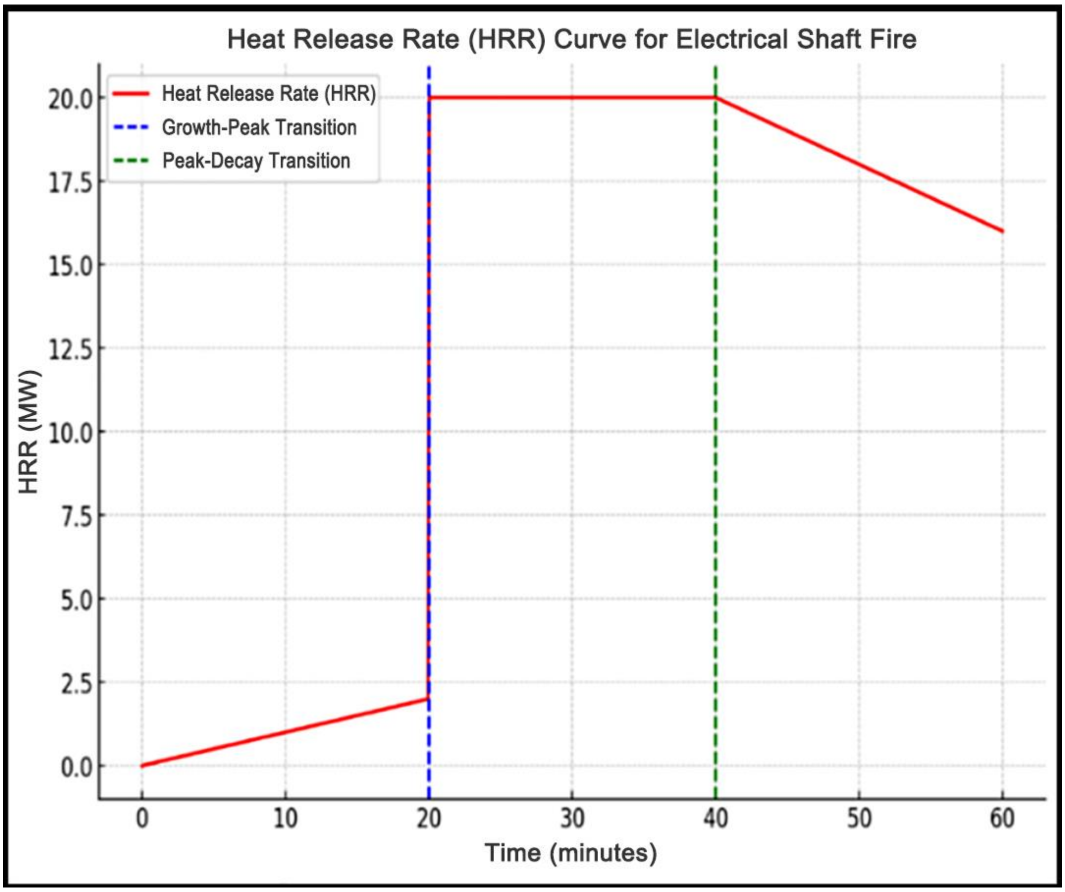


Figure 3. Heat Release rate in an electrical shaft

6.1. Heat Release Rate in an Electrical Shaft [20] [21]

Figure 3, curve in the graph illustrates the Heat Release Rate (HRR) of an electrical shaft fire in a high-rise residential building. It consists of three phases:

1. **Growth Phase (0–20 minutes):** HRR increases linearly at a rate of 0.1 MW per minute, reflecting the initial fire development.
2. **Peak Phase (20–40 minutes):** HRR remains constant at 20 MW, indicating the maximum intensity of the fire.
3. **Decay Phase (40–60 minutes):** HRR decreases linearly at 0.2 MW per minute as the fire diminishes.

Key Insights:

- Peak Fire Hazard (20–40 min): The fire remains at a dangerous intensity for a prolonged period, posing significant evacuation and containment challenges.
- Fire Growth Rate: A slow initial fire growth (0.1 MW/min) indicates that early detection and intervention could significantly limit fire severity.
- Decay Rate vs. Growth Rate: The fire reduces its power twice as quickly (0.2 MW/min) as it increases, which indicates suppression and the exhaustion of fuel in containing the fire.
- Evacuation: During the peak phase, conditions such as high temperatures, density of smoke, and low visibility would hinder the evacuation process, which reaffirms the need for proper smoke control and fire doors.

A brief assessment of the HRR curve brings into focus the importance of early detection, suppression, and smoke control in tall buildings. The constant exposure to the fire conditions at 20MW for a duration of 20 minutes poses evacuation and structural challenges, which call for improved fire resistance of enclosures, efficient ventilation, and suppression systems. As for the further research, the evaluation of NBC-2016 provisions in real-life scenarios will be useful to define the further nuances of the evacuation strategy and enhance the high-rise building fire protection.

7. Study of Fire Dynamics through Pyrosim Simulation

The isosurfaces obtained by the simulation results of Pyrosim, to study the fire dynamics of the temperature, smoke, visibility and carbon monoxide and carbon di oxide at different time of 100s, 250s and 500s are tabulated in Table 4.

7.1. The Study of Carbon Monoxide, Carbon-DI-Oxide, Visibility, Temperature Graphs

In **Table 5**, the graphs obtained from the Pyrosim simulations are plotted for CO and CO_2, Visibility and Temperature of the Fire floor, the above and below floor. The detectors are placed at the escape corridors at 2.1meters from the Finished floor level.

Table 4. The Isosurfaces showing the fire dynamics of the electrical short circuit in the electrical duct as per the actual site fire safety provisions (i.e. without fire door, sprinklers, and mechanical ventilation for the shaft)

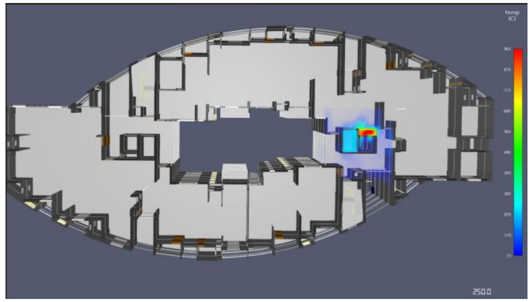
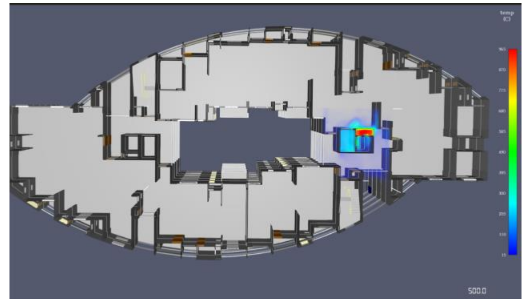
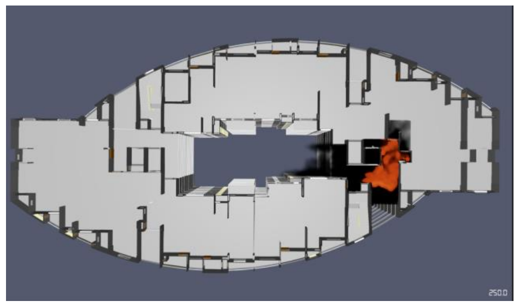
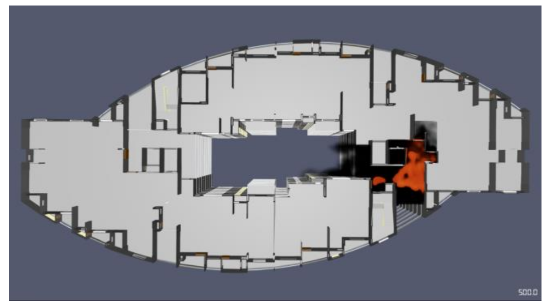
1.	Temperature at 100s	Temperature at 250s	Temperature at 500s
Temperature Isosurface at the fire floor			
Analysis	High temperatures spread rapidly, intensifying heat in shaft.	Temperatures escalate uncontrollably, spreading across fire floor.	High temperatures persist, accumulating severely without cooling mechanisms.
Observation	Without sprinklers, temperatures escalate, increasing fire intensity and spread.		
2.	Smoke at 100s	Smoke at 250s	Smoke at 500s
Smoke Isosurface at the fire floor			
Analysis	Smoke spreads rapidly, no barriers containing a high-density accumulation.	Smoke spreads uncontrollably, impairing air quality across floor and shaft.	Dense smoke engulfs areas, no systems reducing its density.
Observation	Lack of ventilation and fire doors enables unrestricted smoke to spread		
3.	Visibility at 100s	Visibility at 250s	Visibility at 500s

Table 4 continued

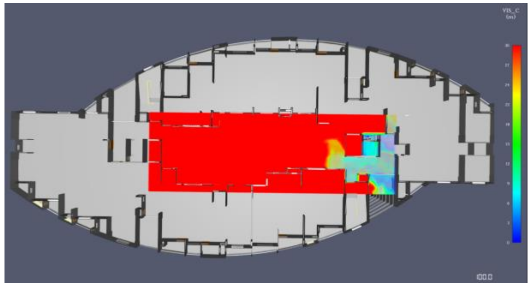
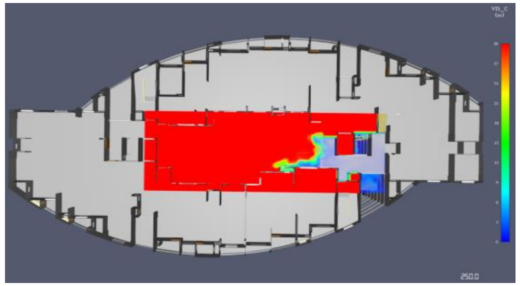
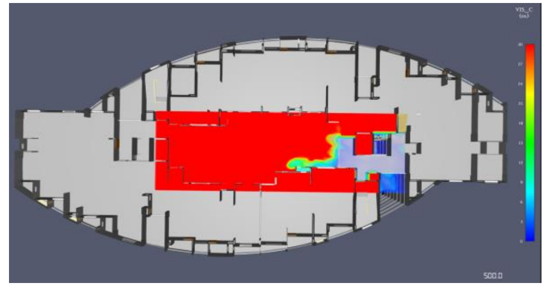
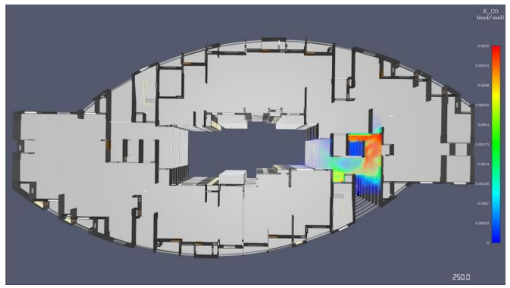
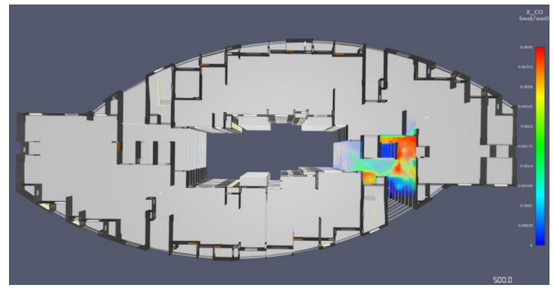
Visibility Isosurface at the fire floor			
Analysis	Visibility deteriorates quickly near the short circuit origin, with significant smoke buildup in shaft.	Visibility reduces to critical levels across the fire floor as smoke accumulates without control mechanisms in place.	Visibility is almost non-existent throughout shaft and adjacent areas, making evacuation extremely hazardous.
Observation	The lack of ventilation and fire doors leads to rapid loss of visibility, exacerbating evacuation challenges.		
4.	CO at 100s	CO at 250s	CO at 500s
CO Isosurface at the fire floor			
Analysis	CO accumulates rapidly, no suppression limiting incomplete combustion effects.	CO spreads widely, accumulating heavily without ventilation to disperse.	CO remains high, trapped in shaft, hindering evacuation and firefighting.
Observation	No ventilation or suppression causes dangerous CO accumulation, risking health.		
5.	CO_2 at 100s	CO_2 at 250s	CO_2 at 500s

Table 4 continued

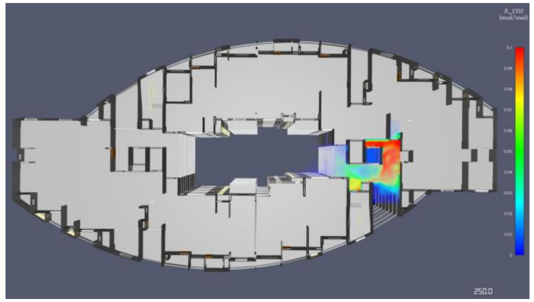
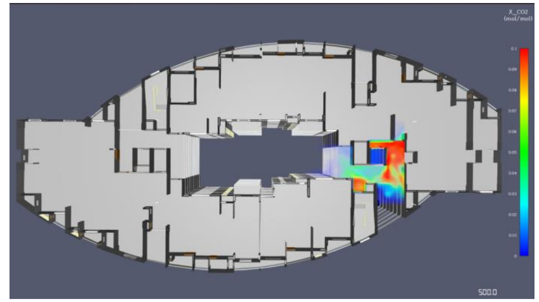
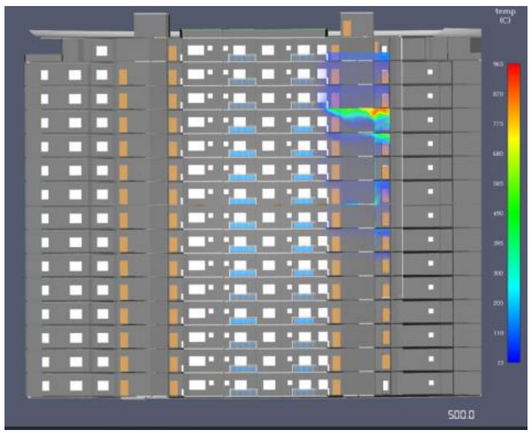
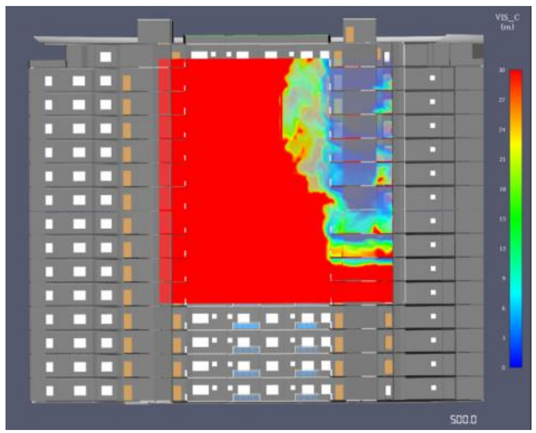
CO_2 Isosurface at the fire floor			
Analysis	CO_2 concentration rises rapidly near fire source due to combustion. No oxygen replenishment accelerates buildup.	CO_2 spreads extensively across fire floor and upward through the shaft, with no barriers to contain its movement.	High CO_2 levels persist, displacing oxygen and increasing the risk of asphyxiation. No extraction systems are in place to remove the gas.
Observation	The lack of fire doors and ventilation leads to uncontrolled CO_2 accumulation, creating hazardous environment		
	temperature	Visibility	Smoke
Section of the Isosurface			
Analysis	Smoke starts to spread rapidly along the shaft, with no barriers to contain its movement.	Smoke spreads uncontrollably both vertically and horizontally, creating dense smoke zones across the floor.	Smoke density remains extremely high, obstructing visibility and reducing air quality throughout the shaft.
Observation	The absence of mechanical ventilation and fire doors allows smoke to spread unchecked, compounding evacuation challenges.		

Table 5. The combined analysis of CO, CO_2, Visibility and Temperature at the fire floor above and below

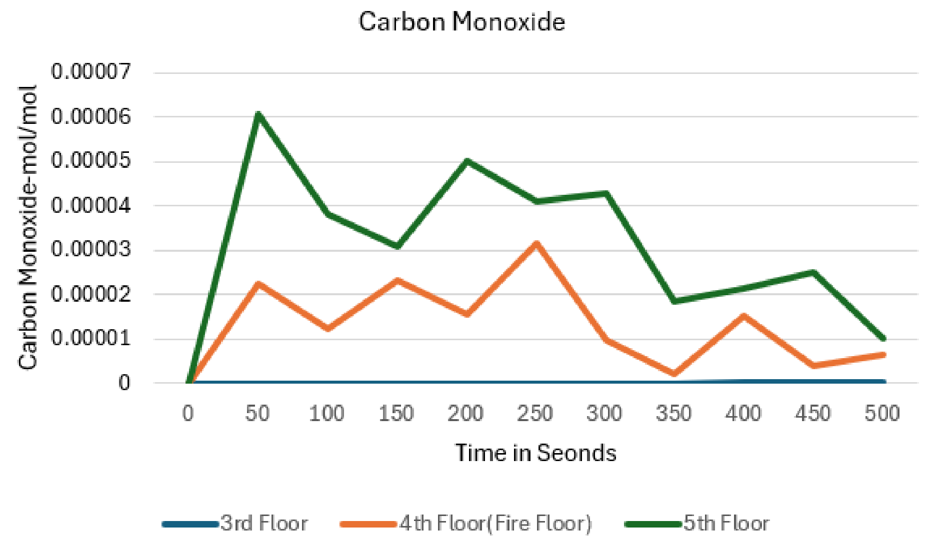
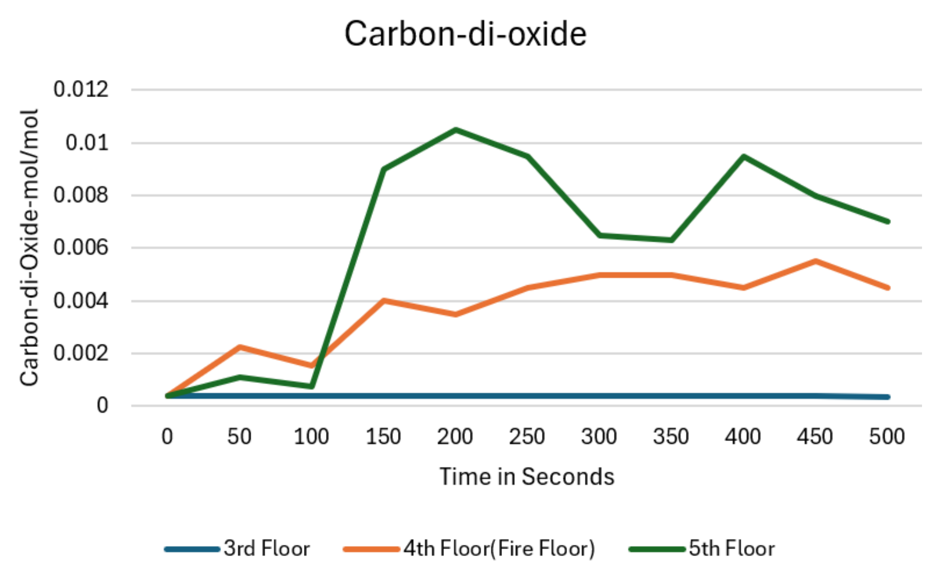
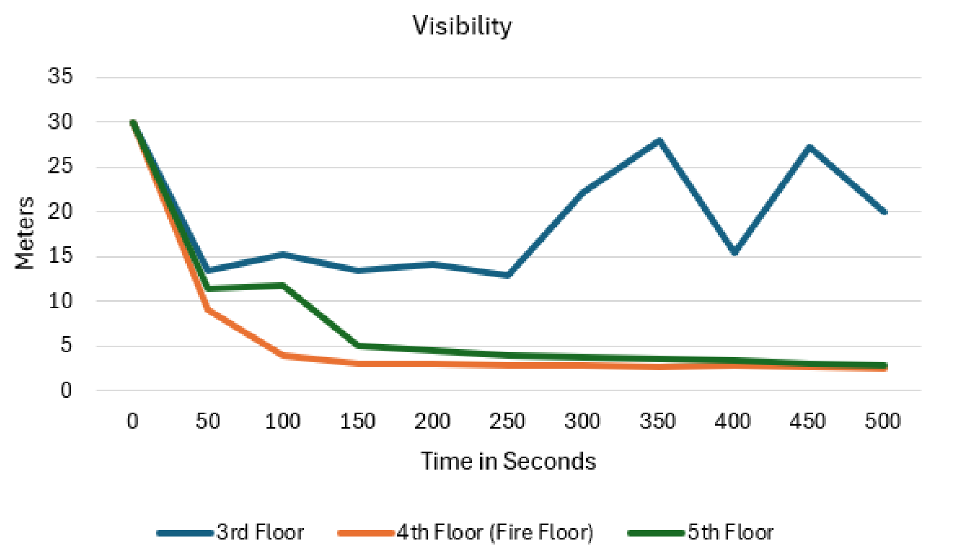
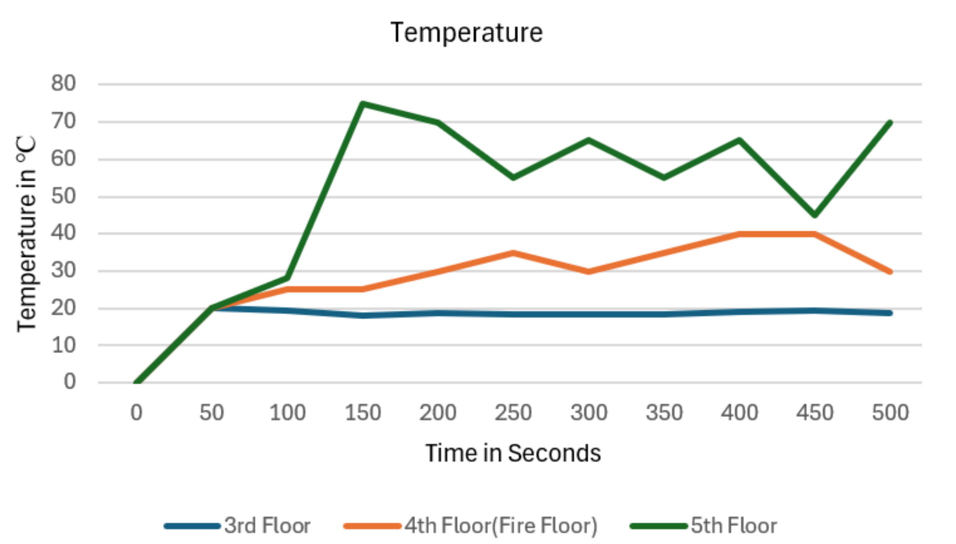
Parameter	**GRAPHS**
CO (Carbon Monoxide)	
Combined Analysis	**4th Floor:** The Carbon monoxide levels reach a maximum of **0.00003mol/mol(30ppm) at the 4th floor**, thus not causing discomfort for the occupants during evacuation. **5th Floor:** Carbon monoxide levels peak at **0.0006 mol/mol(60ppm) at 50 seconds** at the 5th floor above fire floor thus causing discomfort for occupants during evacuation. **3rd Floor:** The 3rd floor, Carbon monoxide levels are low and stable thus causing no difficulty in Evacuation.
Danger Levels & Citations	**50 ppm:** Adverse health effects with long-term exposure; **200 ppm:** Headache after 2-3 hours (OSHA, 2021).[23]
CO_2 (Carbon oxide)	
Combined Analysis	**4th Floor:** The Carbon dioxide levels reach a maximum of 0.005mol/mol(5000ppm) at the 5th floor thus causing discomfort for the occupants during evacuation **5th Floor:** Carbon dioxide levels peak at 0.01mol/mol(10,000 ppm) on the fire floor at **200 seconds**, reflecting intense combustion and complete oxidation **3rd Floor:** The 3rd floor, CO_2 levels are low and stable thus causing no difficulty in Evacuation.
Danger Levels & Citations	**5,000 ppm:** Long-term occupational exposure limit; **10,000 ppm:** Risk of oxygen displacement and asphyxiation (NIOSH, 2019) [24].

Table 5 continued

Visibility (m)	
Combined Analysis	**4th Floor:** Visibility drops below **5 meters** on the fire floor due to high smoke density at **120 seconds**, decreases to 2-3 meters after 200 seconds. **5th Floor:** Visibility drops below **5 meters** at the 5th floor at **150 seconds**, thus causing difficulty in Evacuation. **3rd Floor:** At 3rd floor the smoke remains above 10meters, not causing hinderance in Evacuation till 500 seconds
Danger Levels & Citations	**10 meters:** Impair evacuation and firefighting; critical safety limit for fire scenarios (NFPA, 2019) [25].
Temperature (℃)	
Combined Analysis	**4th Floor:** The temperature reaches a maximum of 40°C upto 500 Seconds, not causing Difficulty for Evacuation. **5th Floor:** Temperatures **exceed 70 ℃** on the fire floor **between (150-200 seconds)**, creating hazardous conditions **3rd Floor:** Below the fire floor, temperatures are stable at 20-25 ℃ due to limited heat transfer, while above the floor, they fluctuate between 30-50 ℃ due to heat dissipation
Danger Levels & Citations	**50 ℃:** Cause discomfort; **70 ℃+:** Risk of heatstroke and burns (who.int) [26]

8. Parameters for Pathfinder Simulation

The fire simulated pyroSim file was imported to Pathfinder to analyze the evacuation of the people. A quantitative analysis was adopted through the questionnaire survey of the residents, where detailed information about the residents was collected like the family size and their ages and if they had been any physically challenged and if they had any formal training or previous experience of fire accident were gathered and the **Table 6** represents the demographic distribution of the residents prepared according to the data collected from the questionnaire. A detailed questionnaire was distributed to a sample size of 324 residents, and the response rate was 78%(253 valid responses and the margin of error was ±4.3%). The Pathfinder simulation was set up according to these details. The walking seeps were assigned as per **Table 7**. Accordingly, simulation results were analyzed and Table 8 indicates the speeds of the residents during evacuation.

8.1. The Study of Evacuation of the Occupants Using Pathfinder Simulation

The fire spread and the evacuation density are discussed in **Table 8**, indicating the slow evacuation due to smoke and bottle necks were the key observations.

8.2. The Study of Congestion during Evacuation Using Pathfinder Simulation

The pathfinder simulations highlight the congestion at 1st, 5th, and 7th floors, the isosurfaces at these floors are tabulated in Table 9 and the evacuation density, and evacuation progress are analysed.

Table 6. Demographic distribution of the residents considered for simulation

Male adult (Age: 15 Years-60 years)	Female adult (Age: 15 Years-60 years)	Children (Age: 5 Years-15 years)	Kids below 5 years	Elderly (above 80 years)	Senior citizens (Above 60 Years-80 Years)	Physically Challenged	Residents with knowledge and training
32%	30%	8%	3%	7%	11%	2%	7%

Table 7. Indicating the evacuation speed for different age groups and genders with the effects of smoke and visibility [27],[28],[29],[30]

Parameter	**Condition**	**Speed (m/s)**	**Source**
Visibility (m)	>10 (Clear)	1.3–1.5	Seike et al., 2021 (Seike et al., 2021)
	5–10	1.0–1.3	
	2–5	0.5–1.0	
	<2	<0.5	
Smoke Density (Cs)	Cs = 0.3 m⁻¹	~1.2	Seike et al., 2016 (Seike et al., 2016)
	Cs = 1.0 m⁻¹	~0.5	
	Cs > 2.0 m⁻¹	Near zero	
Age Group	Children	0.9–1.2 (clear), 0.4–0.7 (smoke)	Seike et al., 2021; Fridolf et al., 2016 (Fridolf et al., 2016)
	Adults	1.3–1.5 (clear), 0.5–1.0 (smoke)	
	Elderly	0.8–1.0 (clear), 0.3–0.5 (smoke)	Lee et al., 2019 (Lee et al., 2019)
Gender	Men	1.4–1.6 (clear), ~0.6 (smoke)	Rahouti et al., 2020 (Rahouti et al., 2020)
	Women	1.2–1.4 (clear), ~0.5 (smoke)	
Behavioral Factors	Panic (General)	+20–50% movement inefficiency	Qi et al., 2020 (Qi et al., 2020)
	Group Assisting	Reduced by ~30%	Rahouti et al., 2020 (Rahouti et al., 2020)

Table 8. Analysis of the evacuation progress in Pathfinder

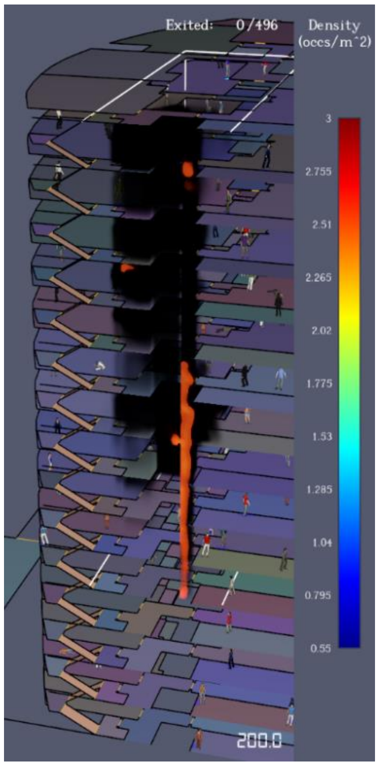
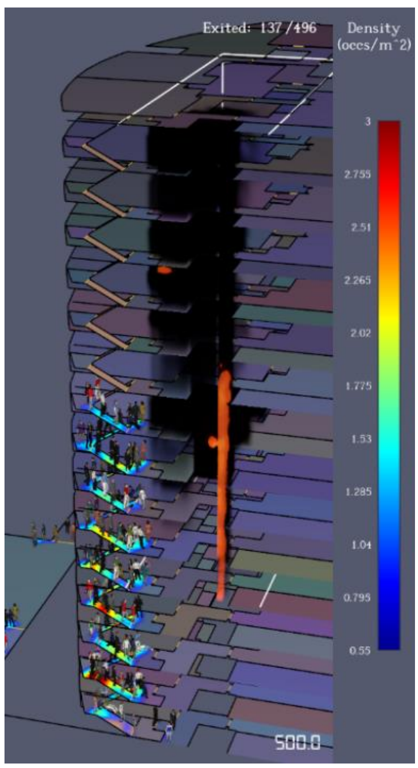
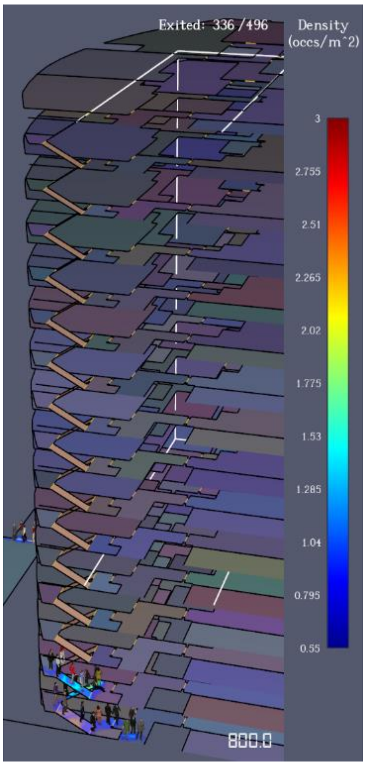
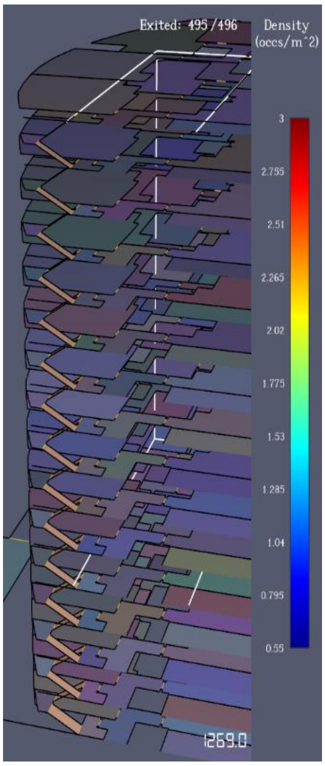
SL. No	Time (s)	Fire Spread and Density	Isosurfaces Depicting Evacuation Density Across Time	Evacuation Progress (occupants evacuated)	Key Observations
1	200	Fire propagates vertically with dense smoke in the shaft. Density exceeds 2 occupants/m^2, creating hazardous zones.		0/496	High congestion in stairwells impedes evacuation.
2	500	Fire intensifies with severe smoke accumulation. Congestion in stairwells remains critical.		137/496	Dense smoke and bottlenecks slow evacuation, posing significant risks to remaining occupants.

Table 8 continued

3	800	Smoke begins to stabilize, but congestion persists in some areas.		336/496.	Evacuation improves, but exposure risks remain for the upper floors.
4	1260	Smoke density was reduced significantly, with improved stairwell flow.		495/496	The near-complete evacuation was achieved, but delays indicate the need for improved pathways and fire control.

The results emphasize the **critical role of smoke control, congestion management, and evacuation efficiency** in high-rise fire scenarios. The prolonged evacuation times suggest that **current fire safety measures are insufficient**, reinforcing the need for **better fire-rated doors, stairwell pressurization, and optimized evacuation strategies.**

Table 9. The isosurface showing the congestion at different floors during the evacuation.

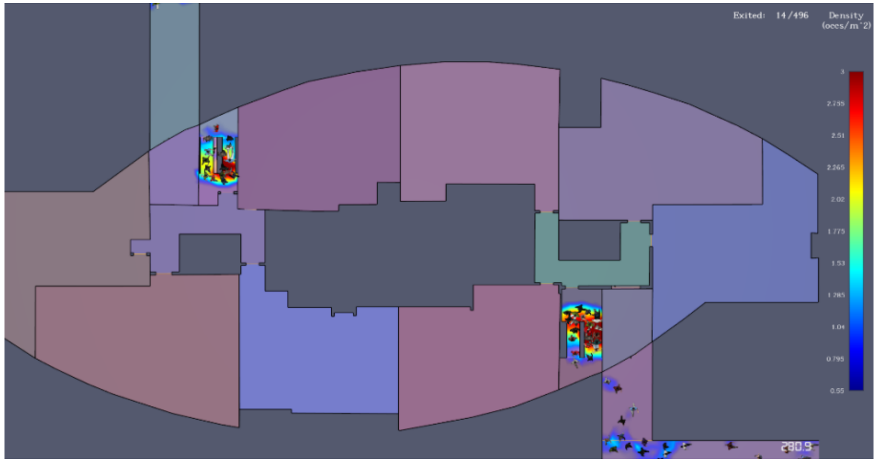
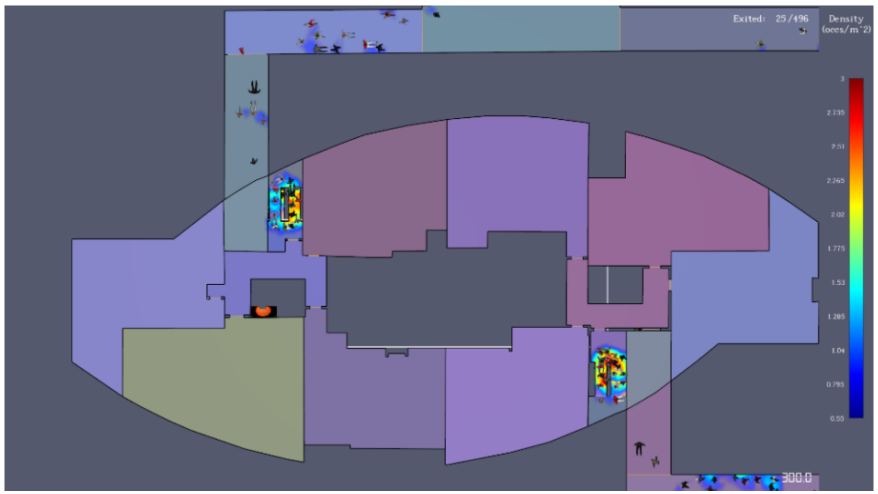
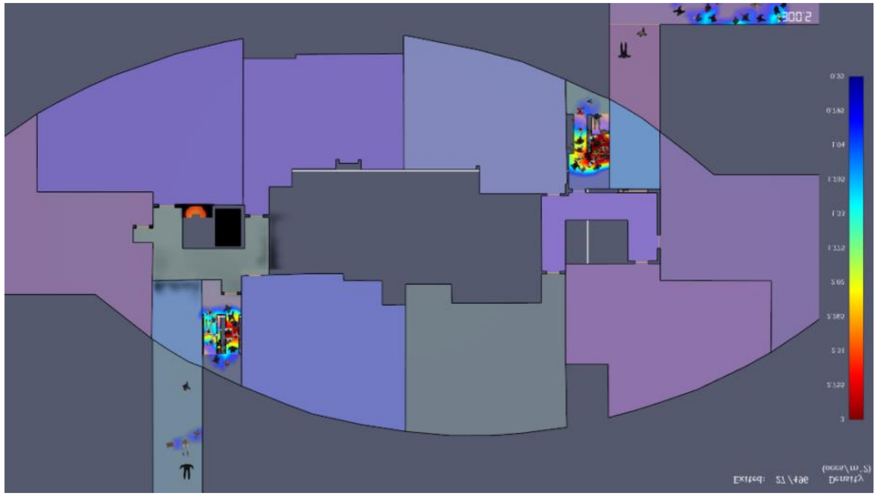
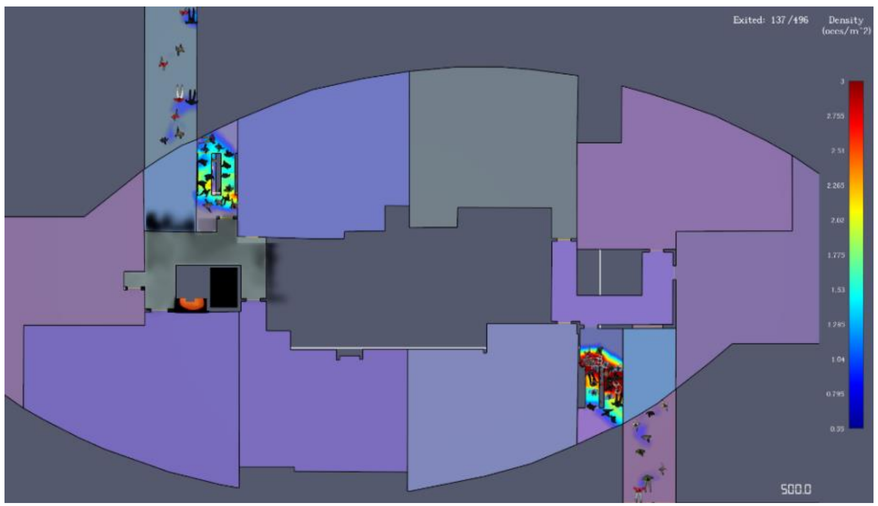
Congestion on 1st floor at 280 seconds	**Evacuation Density**	**Evacuation Progress**	**Key Observations**
	Exceeds **1.5 occupants/m ²** near exits.	The limited number of occupants exited.	Bottlenecks delay evacuation; improved exit pathways are needed.
Congestion on the 5th floor at 300 seconds	**Evacuation Density**	**Evacuation Progress**	**Key Observations**
	Spikes above **2.5 occupants/m ²**near stairwells.	Upper-level flow complicates movement.	High congestion increases crowding risks and evacuation delays.
Congestion on the 7th floor at 300 seconds	**Evacuation Density**	**Evacuation Progress**	**Key Observations**

Table 9 continued

	Approaches **2.0 occupants/m ²**at stairwells.	Intermediate floors face bottlenecks.	Highlights need for optimized intermediate exits.
Congestion on the 7th floor at 500 seconds	**Evacuation Density**	**Evacuation Progress**	**Key Observations**
	Reduces near stairwells but persists locally.	The majority of occupants evacuated.	Reduced congestion allows better evacuation but requires traffic flow management.

9. ASET and Reset

The ASET (Available Safe Egress Time) and RSET (Required Safe Egress Time) are critical metrics for evaluating the safety of building evacuations during fire scenarios. In this study, PyroSim was used to simulate fire dynamics including smoke propagation, carbon monoxide (CO) and carbon dioxide (CO_2) concentrations, temperature rise, and visibility reduction, all important factors in determining ASET. ASET represents the time available for occupants to evacuate before conditions become untenable, such as when visibility drops below 10 meters, CO levels exceed 50 ppm, or temperatures exceed human tolerances [31],[32]. Pathfinder simulations were also used to calculate RSET, which includes human behavior, building geometry, and walking speeds during evacuation. RSET with pre-movement time (time for occupants to recognize and respond to the fire alarm) and travel time, is a function of walking speeds (~1.2 m/s on flat surfaces and ~0.5 m/s on stairs), congestion at exits, and evacuation flow [10],[11],[12]. For evacuation safety, ASET must exceed RSET, ensuring occupants can safely evacuate before conditions deteriorate [33],[34],[35]. The simulations provided a comprehensive analysis of fire behavior and evacuation efficiency, highlighting the interplay between fire dynamics and human response in determining safe egress times.

ASET Calculation:

- **Time to untenable conditions (visibility < 10m): 110 seconds**

RESET Calculation:

- **RESET = Pre-Movement time + Travel time + Safety Margin: 1272 Seconds**

a) Pre-movement Time = Detection Time + Alarm Time + Response Time

b) Travel Time Formula:

Travel Time = Walking Speed/Travel Distance

c) Safety Margin = ASET−RSET

Hence the simulation results indicate that the RESET>ASET with the current fire safety provisions as per the actuals on-site

The same simulation is repeated with the provision of the fire doors for the electrical shafts and with mechanical ventilation and the results were analysed, the isosurfaces obtained are shown in **Table 10.**

Table 10. Showing the Isosurfaces with the Analysis and Observation of the simulation after the Installations According to NBC-2016

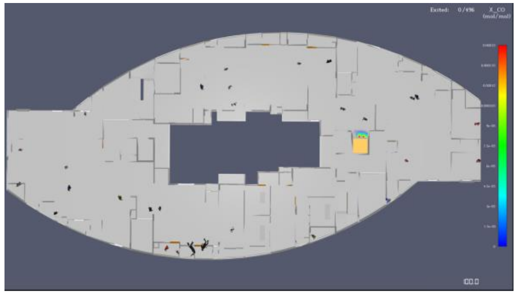
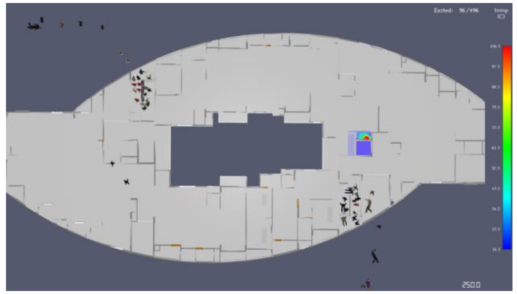
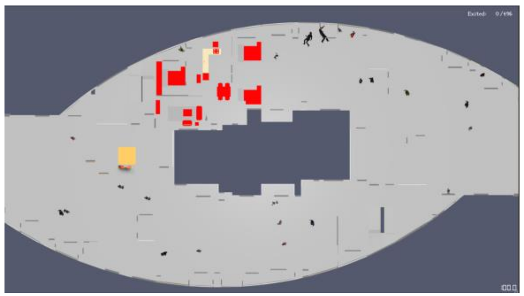
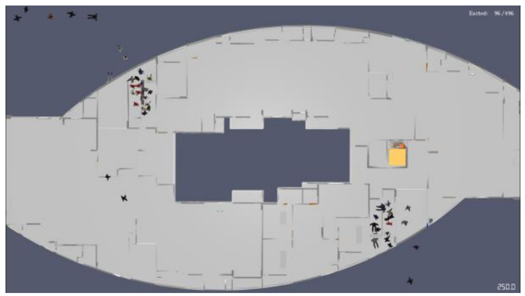
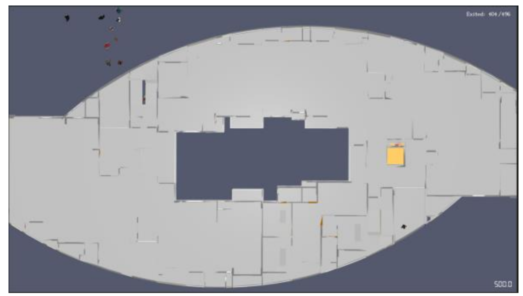
1.	Temperature at 100s	Temperature at 250s	Temperature at 500s
Temperature Isosurface at the fire floor			
Analysis	High temperatures localized near the short circuit origin. Heat is concentrated in small areas (red/yellow zones).	Temperature spreads across fire floor, indicating fire growth. Mechanical ventilation moderates heat buildup; sprinklers contribute to slight cooling.	Temperatures stabilize, with cooler areas due to sprinklers. Hot zones persist near the fire source.
Observation	Sprinklers reduce peak temperatures but cannot fully suppress fire within the shaft.		
2.	Smoke at 100s	Smoke at 250s	Smoke at 500s
Smoke Isosurface at the fire floor			
Analysis	Smoke localized near the short circuit origin, starting to spread vertically along the shaft.	Smoke spreads extensively across the floor, with mechanical ventilation dispersing and diluting density in some areas.	Smoke density remains high near the shaft. Accumulation in distant areas indicates ventilation inefficiency.
Observation	Mechanical ventilation moderates smoke spread but does not fully clear smoke near the fire source.		
3.	Visibility at 100s	Visibility at 250s	Visibility at 500s

Table 10 continued

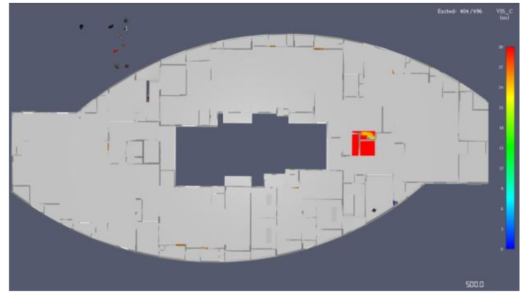
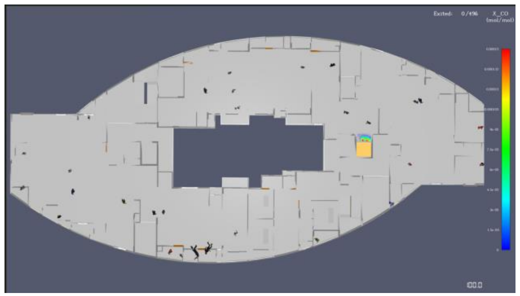
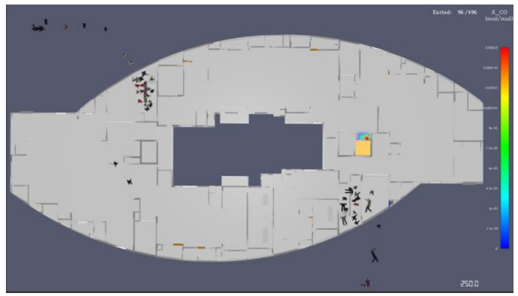
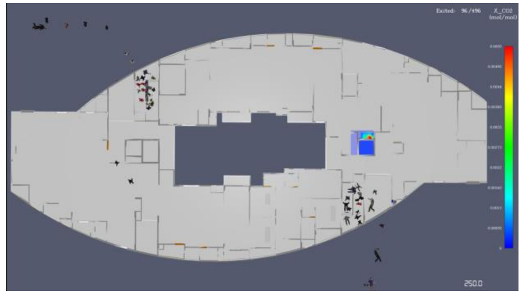
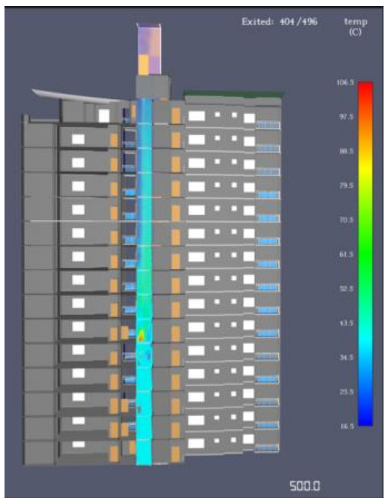
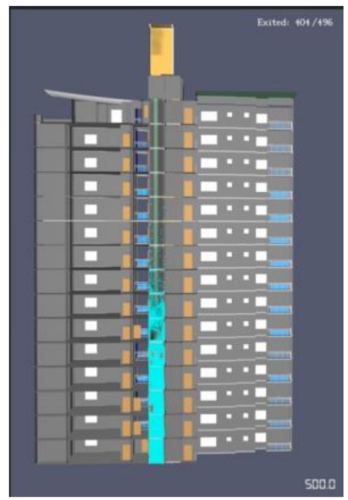
Visibility **Isosurface at the fire floor**			
Analysis	Visibility begins to decrease near the short circuit origin but remains acceptable in most regions.	Visibility deteriorates near the shaft and pathways due to increasing smoke density, with low-visibility zones appearing.	Visibility is critically low near the shaft and adjacent zones, with near-zero visibility affecting evacuation.
Observation	Mechanical ventilation delays visibility loss but is insufficient to control critical low visibility near the shaft.		
4.	CO at 100s	CO at 250s	CO at 500s
CO **Isosurface at the fire floor**			
Analysis	CO concentration is minimal, localized near the short circuit origin, indicating the initial stages of combustion.	CO spreads across a larger area. Ventilation reduces accumulation in some regions but remains high near the shaft.	CO remains concentrated in specific areas despite ventilation and sprinkler systems reducing spread.
Observation	Sprinklers and ventilation partially control CO but cannot fully eliminate toxic gases.		
5.	CO_2 at 100s	CO_2 at 250s	CO_2 at 500s

Table 10 continued

CO_2 Isosurface at the fire floor			
Analysis	CO_2 concentration is initially low, indicating early combustion with minimal oxygen depletion.	CO_2 levels rise significantly and spread horizontally, with higher concentrations near the fire source.	CO_2 continues to accumulate but is dispersed more due to ventilation. High levels pose a risk of oxygen displacement.
Observation	Ventilation disperses CO_2, but its accumulation poses a significant hazard for occupant asphyxiation.		
6.	Temperature	Visibility	Smoke
Section of the Isosurface with the sprinklers and Mechanical ventilation			
	The temperature within the shaft remains between 30 ℃ and 35 ℃, effectively controlled by the sprinklers, which help regulate heat buildup and limit fire spread.	The visibility in the shaft is maintained at 6 meters, ensuring it does not obstruct the evacuation process.	With the provision of fire-rated doors in the electrical shaft, smoke containment is effectively maintained, preventing its spread to other areas.

10. Pyrosim Simulation Results-after the Installation of the Fire Doors, Srinklers and Mechanical Ventilation for the Electrical Shafts According to NBC-2016

10.1. The Study of Evacuation of the Occupants Using Pathfinder Simulation after the Installations According to NBC-2016

The results of the evacuation of the residents using pathfinder the isosurfaces showing the evacuation density across 200s, 400s, 600s and 746s are discussed in Table 11.

10.2. The Study of Congestion during Evacuation Using Pathfinder Simulation after the Installations According to NBC-2016

The congestion during evacuation is analysed using the isosurfaces from the pathfinder at 6th floor at 200s, 5th floor at 300s, 3rd floor at 200s and at 9th floor at 250s as shown in Table 12 and the analysis is discussed with key observations of the congestion at different floors.

Table 11. Analysis of Isosurfaces Depicting Evacuation Density Across Time

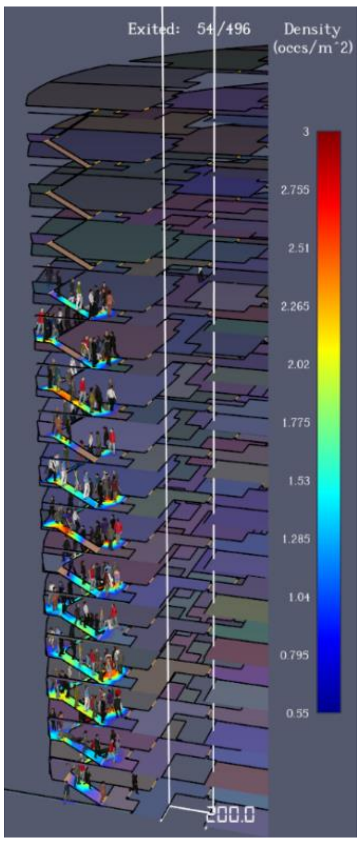
Time (s)	Evacuation Density	Isosurfaces Depicting Evacuation Density Across Time	Evacuation Progress (occupants evacuated)	Key Observations
200	High density in stairwells, exceeding 2.0 occupants/m^2 Bottlenecks form near critical junctions.		54/496	Stairwells experience severe congestion, delaying evacuation process.

Table 11 continued

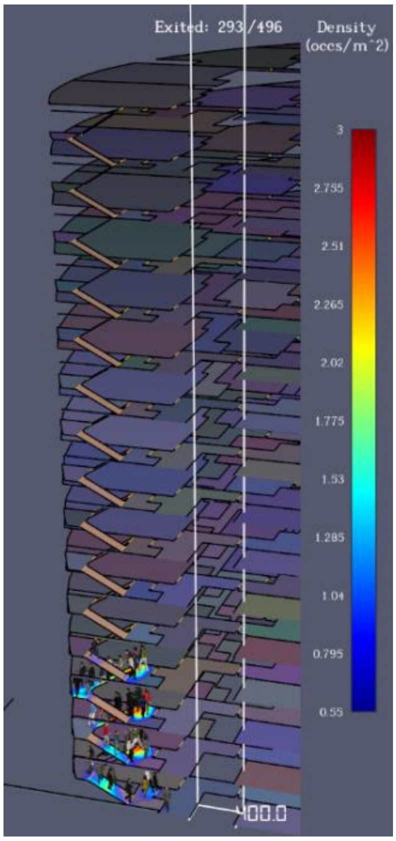
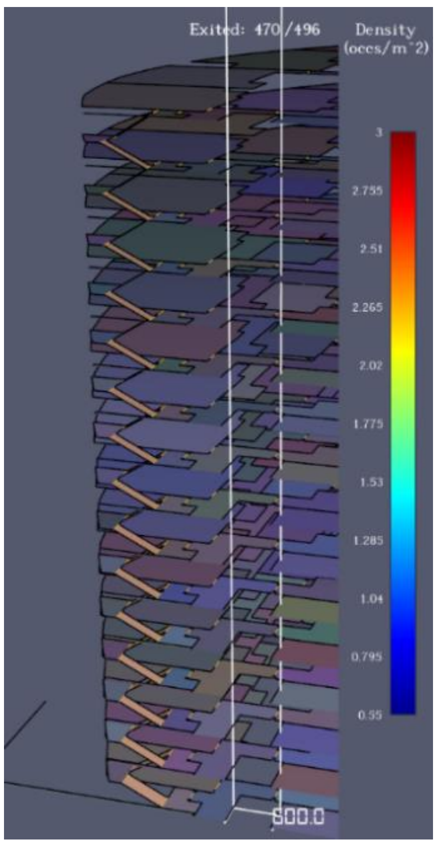
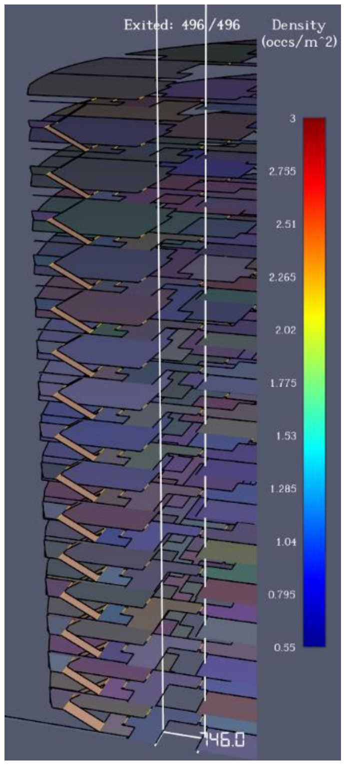
400	Density stabilizes slightly but remains critical in some stairwell zones. Pockets of congestion persist.		293/496	Evacuation flow improves as congestion reduces, but delays are still observed in upper-level clearances.
600	Density further reduces across most floors, with near-normal levels (<1.5 occupants/m^2) observed in stairwells.		470/496	Significant improvement in flow efficiency; most floors are cleared, but a few bottlenecks persist.

Table 11 continued

746	Density normalizes completely. All stairwells and evacuation routes are clear.		496/496	Complete evacuation achieved; analysis highlights the need for improved initial flow management to reduce delays.

The evacuation analysis reveals that **high congestion** occurs in the **early stages (200s),** with stairwell densities exceeding **2.0 occupants/m^2,** causing significant delays. By **400s,** congestion stabilizes, but bottlenecks persist in upper levels, slowing evacuation. At **600s,** density normalizes across most floors, leading to **improved flow efficiency,** with only minor delays. Complete evacuation is achieved at **746s,** emphasizing the need for **better initial flow management** to **reduce early-stage congestion and improve overall evacuation efficiency.**

Table 12. The isosurface shows the congestion at different floors during evacuation

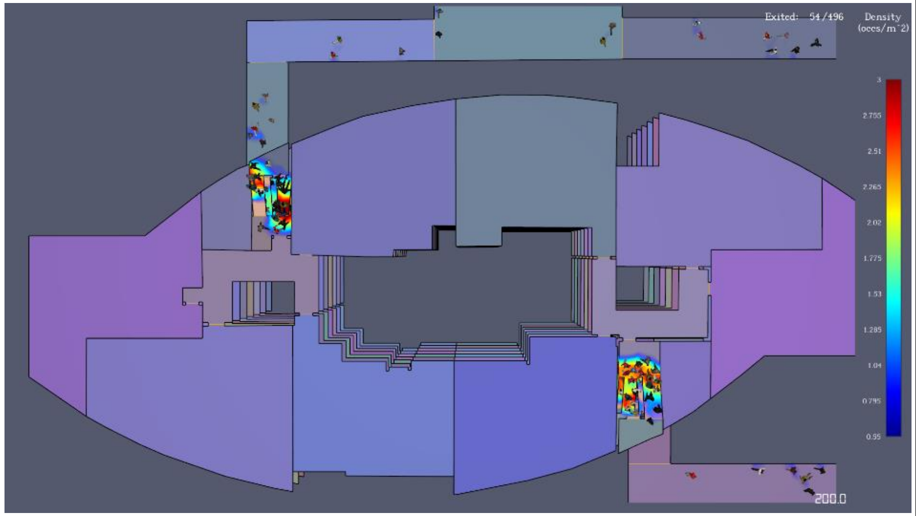
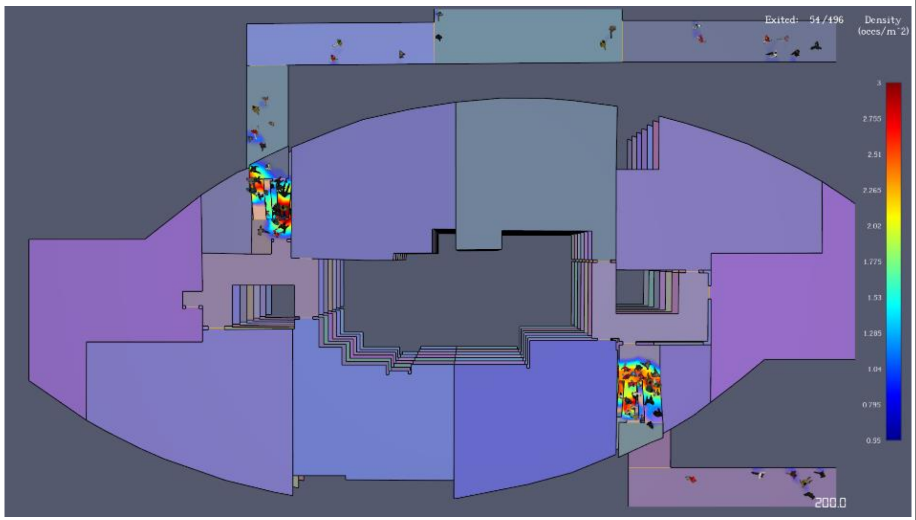
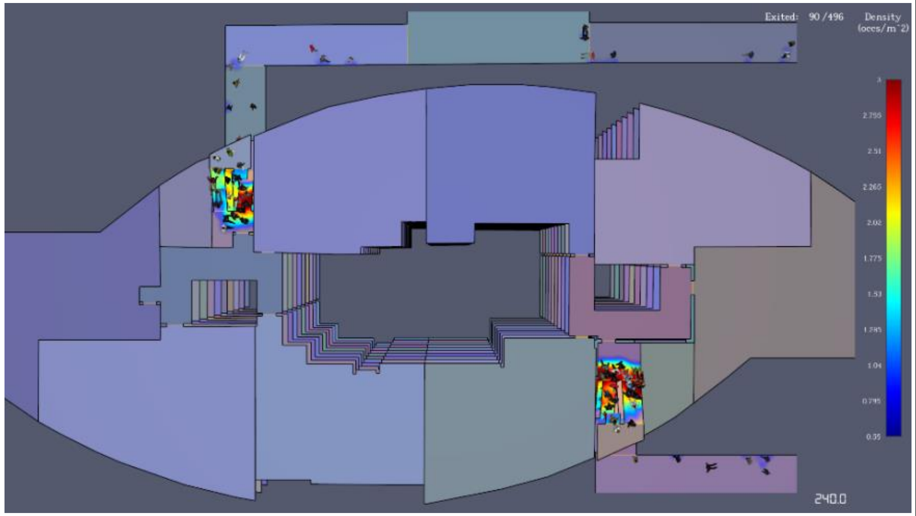
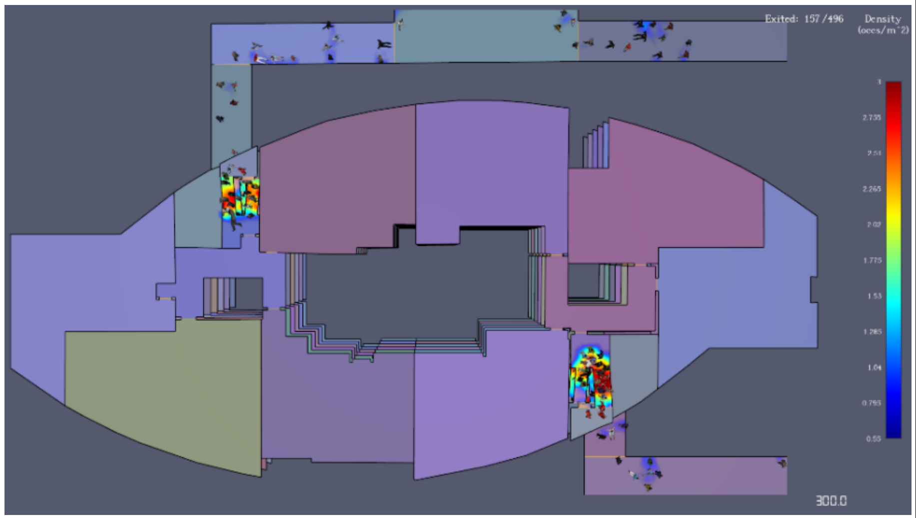
Congestion on the 3rd floor at 200 seconds	**Evacuation Density**	**Evacuation Progress**	**Key Observations**
	Moderate congestion was observed near stairwell and pathway intersections.	Limited progress due to lower evacuation flow from upper levels.	Congestion indicates insufficient distribution of evacuees across routes.
Congestion at 6th floor at 200 seconds	**Evacuation Density**	**Evacuation Progress**	**Key Observations**
	High congestion near stairwell entries, density exceeding 2.0 occupants/m ²	Minimal progress; occupants still gathering near exits.	Significant bottlenecks delay evacuation; critical pathways are obstructed.
Congestion on the 9th floor at 250 seconds	**Evacuation Density**	**Evacuation Progress**	**Key Observations**

Table 12 continued

	Moderate congestion at stairwells; density stabilizing below 2.0 occupants/m^2	Improved progress as upper floors begin to clear.	Evacuation flow improves but is still constrained by intermediate floor bottlenecks.
Congestion on the 5th floor at 300 seconds	**Evacuation Density**	**Evacuation Progress**	**Key Observations**
	High density (>2.5 occupants/m^2) near stairwell zones; severe bottlenecks.	Progressive evacuation with intermediate floors contributes to congestion.	Crowding impacts evacuation efficiency; further mitigation measures are required.

The evacuation congestion analysis highlights significant bottlenecks near stairwell entries, particularly on the **6th and 5th floors**, where occupant density exceeded **2.0–2.5 occupants/m^2**, delaying evacuation. Moderate congestion was observed on the **3rd and 9th floors**, improving as upper levels cleared, but intermediate floor bottlenecks persisted. These findings indicate the need for **wider stairwells, additional escape routes, and improved evacuation flow management** to prevent critical delays. Optimizing stairwell usage and implementing **staggered evacuation strategies** can significantly enhance safety in high-rise residential buildings.

11. Results and Discussion

The ASET AND RESET values obtained from the simulation results are compared with the actuals based on site conditions and with the enhanced safety margin by enhancing the fire provisions as per NBC 2016, as presented in Table 13.

Fire-rated doors, sprinklers, and mechanical ventilation systems were installed in the electrical shaft due to electrical short circuits, and these measures enhanced the fire characteristics. These measures helped to contain the fire from reaching the evacuation corridors, hence minimising hindrances to the evacuation channel. The simulation analysis of Pathfinder also shows that the RSET reduced from 1272 to 746, which proved the efficiency of fire safety provisions as per the NBC-2016 regulation.

Despite these improvements, however, challenges such as congestion, bottlenecks in evacuation routes, and high occupant density during evacuation still impede the process. In addition, there is the electrical shaft that is saturated with carbon monoxide (CO) and carbon dioxide (CO_2), and this poses a danger to occupants in the building during evacuation.

The measures have been suggested to enhance evacuation effectiveness and mitigate the general risk of fire, but they do not eliminate fire risks to the residents of a house. Therefore, for the high-rise residential buildings, additional enhancement is required for the ventilation system, control of congestion, and fire safety measures.

This research fills the gaps in the existing knowledge about fire safety by targeting the special issues that are connected with electrical shaft fires in high-rise residential buildings. Contrary to the previous works that have excluded these small areas, this work utilises PyroSim and Pathfinder models to analyse the fire spread and movement of people.

11.1. Comparison with Previous Research

Previous studies emphasized the impact of architectural features on evacuation outcomes but overlooked electrical shaft fires, which pose unique challenges due to their vertical structure[8],[21]. This research models fire propagation in electrical shafts, analyzing smoke spread, visibility, and evacuation efficiency. The previous studies have highlighted the benefits of pressurized staircases [9]; this study assesses enclosed fires and shows that NBC-2016 provisions, such as fire-rated doors and sprinklers, reduce RSET. By integrating fire dynamics and egress simulations in PyroSim and Pathfinder, it identifies ongoing issues with bottlenecks and highlights the need for improved egress routes and occupant training.

11.2. Addressing Research Gaps

This work is among the few that employ advanced tools like PyroSim for simulating fire scenarios with human behaviour modelling in electrical shaft fires. Thus, the research provides new knowledge that has not been discussed before when differentiating between ASET and RSET under real-world and improved safety conditions. The evaluation of the deviations from NBC-2016 concerning unpressurized staircases and the lack of sufficient landings also shows practical problems that were not discussed in the prior studies.

Also, the representation of fire parameters using isosurface, such as temperature, smoke density, and visibility over time, gives an easy way of analysing the fire pattern. These visualisations are useful in decision making, and the development of this paper adds to the body of knowledge.

11.3. Contributions to the Field

This research proves the efficiency of NBC-2016 provisions and reveals the consistently observed problems in the electrical shaft fire cases. It is a valuable study in the field of performance-based fire design of high-rise buildings since it offers a detailed account of fire development and evacuation response. The results indicate the need for such innovations as innovative ventilation, specific congestion control, and improved suppression technologies that form the basis for further research in high-rise fire safety.

Table 13. A comparative table summarizing the key results from the simulations, providing a direct comparison of ASET and RSET under different conditions.

Scenario	ASET (seconds)	RSET (seconds)	Safety Margin (ASET - RSET)	Key Observations
Actuals as per site	110	1272	-1162	RSET exceeds ASET; unsafe evacuation.
With NBC-2016 Provisions	1,100	746	+354	Improved safety margin; reduced congestion.

12. Conclusions

This research focused on the fire behaviour and evacuation difficulties presented by electrical shaft fires in high-rise residential buildings. The studies showed that under current conditions, smoke, CO, CO_2, and high temperatures significantly hinder safe evacuation, and RSET > ASET. The provisions of NBC-2016 safety measures, such as sprinklers, fire-rated doors, and mechanical ventilation, helped minimize the evacuation time and enhanced fire safety conditions. However, these measures did not eliminate problems such as congestion, bottlenecks, and high dangerous gas levels, which indicates that electrical shaft scenarios are still dangerous.

The new findings of this research are the integrated PBFD analyses of fire development and human movement in enclosed stairwells and vertical corridors. Through the use of isosurfaces and comparative ASET-RSET views, the research uncovers areas that are not adequately addressed by current safety strategies. The conclusions pinpoint the need to improve the ventilation systems, increase the fire safety measures, and seal off the compartments to meet the safety needs and ensure the safety of the occupants in case of fire. These are important in developing better measures that can be put in place to address the factors that are characteristic of high-rise residential buildings.

13. Recommendations for Improving the Evacuation

Some of the specific suggestions are the upgrading of the ventilation systems, better fire fighting measures, and the usage of IoT technology for monitoring the spread of fire and the location of the occupants. Besides, it is also important to train the occupants of buildings and to ensure that the exit routes are effectively designed to reduce congestion and enhance evacuation.

14. Limitations and Future Work

This work also relies on certain assumptions of constant environmental and material properties in a given environment, which may not hold in a real-world setting. Another drawback of the computational analysis was the limitations in the size of the grid that was used to model the conditions of the experiment. Further studies should focus on dynamic analysis of human behaviour and compare the results with physical experiments and also expand the studies to include commercial and multi-purpose building.

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