Benefits of Compartmentalization for Fire Safety in High-Rise Buildings

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Abstract

Purpose: This paper aims to evaluate the practical benefits of compartmentalization for fire safety in high-rise structures, with a focus on enhancing safety protocols in the construction industry. As high-rise buildings increasingly become iconic landmarks worldwide, the need for effective fire protection measures is paramount.

Design/Methodology/Approach: The study employed a snowball sampling method and a survey design, engaging several construction industry specialists in Gauteng. Data was collected through a structured questionnaire and analysed using percentages, frequency mean scores, and exploratory factor analysis.

Findings: The study identified key benefits of compartmentalization, categorized into the protection of human life, property, and the environment. High-priority benefits include safeguarding escape routes, containing the spread of fire, providing firefighters with additional time to control the blaze, and maximizing evacuation time. These measures also help minimize the risk of fire spreading to adjacent buildings, thereby enhancing overall fire safety in high-rise structures.

Practical Applications: The findings underscore the critical role of compartmentalization in improving fire safety protocols within high-rise building projects. By implementing these measures, construction professionals can better protect occupants, assets, and the surrounding environment, making these strategies essential for modern urban development.

Type of Paper: Empirical research paper

Keywords: Building Compartmentalization, High-Rise Structures, Fire Protection, Building Envelope

1. Introduction

Passive fire safety measures, such as compartmentalization, play a critical role in enhancing the fire safety of high-rise buildings. Compartmentalization involves dividing a building into smaller sections or compartments, each with its own fire-resistant barriers, such as fire-rated walls and floors, to contain the spread of fire and smoke within a limited area (Rasbash, 2010). This strategy not only helps to prevent the rapid spread of fire but also provides occupants with additional time to evacuate safely and emergency responders with better access to extinguish the fire (Purkiss & Greenhalgh, 2014). Research has shown that compartmentalization significantly reduces the risk of fire-related fatalities and property damage in high-rise buildings (Babrauskas & Peacock, 2007). For example, a study by Purkiss and Greenhalgh (2014) found that buildings equipped with compartmentalization systems experienced lower rates of fire spread and reduced fire severity compared to those without such measures. Similarly, research conducted by Babrauskas and Peacock (2007) demonstrated that compartmentalization can effectively limit fire growth and prevent the development of large-scale fires in multi-story structures.

Furthermore, compartmentalization aligns with the principles of sustainable building design by minimizing the environmental impact of fire incidents. By confining fires to localized areas, compartmentalization helps to reduce the release of toxic gases and smoke into the atmosphere, mitigating air pollution and minimizing the ecological footprint of fire events (CIBSE, 2012). In addition to its role in fire prevention and life safety, compartmentalization can also contribute to the overall resilience of high-rise buildings against fire hazards. By compartmentalizing critical building systems, such as electrical and mechanical equipment, compartmentalization helps to maintain essential services during a fire emergency, thereby enhancing the building's ability to withstand and recover from fire-related disruptions (BSI, 2015).

Given the critical importance of compartmentalization in enhancing fire safety, this paper aims to evaluate its practical benefits specifically for high-rise structures. The following sections will explore the theoretical underpinnings of compartmentalization, analyze its impact on fire safety through empirical data collected from industry specialists, and discuss the broader implications of these findings for construction practices. The paper concludes with recommendations for incorporating compartmentalization into modern building design to improve safety protocols and promote resilience in high-rise developments.

2. Literature review

2.1 Building Compartmentalization Overview

Building compartmentalization is a critical passive fire safety strategy that involves dividing a structure into fire-resistant compartments, which can consist of one or more stories, rooms, or areas to contain fires effectively (Fire Protection Association [FPA], 2008). This is achieved through the use of firewalls, protected areas, compartment flooring, and ensuring adequate structural stability (Ueno & Lstiburek, 2015). Compartmentalization addresses multiple aspects of fire safety, including occupant protection, door quality, and structural durability in high-rise buildings.

Recent advancements in building science have expanded the methods of compartmentalization. Li (2018) identified three distinct techniques: unit compartmentalization, floor-by-floor compartmentation, and double compartmentalization. Unit compartmentalization involves enclosing each side of a compartment with fire-resistant barriers, which helps in maintaining air quality, preventing smoke transfer, and enhancing occupant comfort (Li, 2018). Floor-by-floor compartmentation, which is more common in commercial structures, reduces the stack effect—vertical air movement that can exacerbate fire spread—by ensuring airtightness between levels (Li, 2018). Lastly, double compartmentalization combines these two methods, providing comprehensive fire containment but requiring significant investment in sealing internal components (Li, 2018).

The importance of proper compartmentalization in high-rise structures cannot be overstated, as it is crucial for managing smoke, fire, odors, sound, and space heating costs (Hill, 2005; Ueno & Lstiburek, 2015). Recent studies by Finch et al. (2021) have further demonstrated that compartmentalization not only enhances occupant comfort by regulating air temperature and humidity but also reduces the need for extensive ventilation equipment, thereby lowering energy consumption and operational costs. These benefits highlight the continued relevance of compartmentalization in modern high-rise construction, emphasizing the need for ongoing innovation in this area.

2.2 Benefits of Compartmentalizing

The benefits of fire safety measures, both active (e.g., sprinkler systems) and passive (e.g., compartmentalization), are well documented and include life safety, property protection, environmental protection, and business continuity (Qianli & Wei, 2022). Compartmentalization, specifically, is designed to prevent the rapid spread of fire, thereby protecting escape routes and ensuring structural stability during a fire event (Knight, 2007). This strategy also helps in regulating smoke, minimizing fire impact on building fabric, and preventing the entrapment of occupants (A-D-B, 2020).

Recent research has highlighted the role of compartmentalization in maximizing evacuation time and enhancing egress during fire emergencies. Watts et al. (2020) found that compartmentalizing a building into separate fire zones allows for safer evacuation routes, as fire can be contained within a specific area, protecting other parts of the building. This approach has been shown to be particularly effective in high-rise structures, where evacuation time is critical. Furthermore, the integration of occupant health, safety, and comfort in building design has become increasingly important. Studies by Behm and Hock (2021) and Opoku and Ahmed (2020) have emphasized that sustainable building practices, including compartmentalization, can lead to significant cost savings over the building's lifecycle. These studies also noted that fire safety systems, which can account for up to three percent of total building costs, are vital for protecting high-value properties and goods, often reducing potential losses to acceptable levels.

Lastly, compartmentalization contributes to energy efficiency and capital savings. Unlike active fire systems that require activation, compartmentalization functions passively, containing fires and providing crucial time for emergency personnel to respond (Knight, 2022). This passive approach not only enhances safety but also reduces long-term operational costs, making it a key consideration in the design and construction of high-rise buildings.

3. Research methodology

This study employed a quantitative research design to evaluate the benefits of compartmentalization for fire protection in South African high-rise buildings. Quantitative research involves the collection and analysis of numerical data, allowing for objective assessment and generalization of findings (Punch, 2005). This approach is particularly suitable for studies that require data from a large population sample, as it facilitates the use of standardized procedures and replicable study designs (De Vos et al., 2005).

3.1 Sampling Method

The study utilized a snowball sampling method, a non-probability sampling technique often used in research where it is difficult to locate participants with the necessary experience or expertise. In this approach, initial participants, who were construction industry professionals, were identified and asked to refer additional participants within their network. This method was particularly effective for reaching professionals such as quantity surveyors, engineers, architects, and construction managers who had experience in high-rise building construction in Johannesburg, South Africa. Snowball sampling ensured that the sample included individuals with relevant expertise, thereby enhancing the study's reliability.

3.2 Questionnaire Design

The primary data collection tool for this study was a structured questionnaire. The questionnaire was designed to gather detailed information on the respondents' experiences, perceptions, and knowledge regarding compartmentalization in high-rise buildings. It was divided into several sections, each targeting specific aspects of the study.

- **Section A: Demographic Information**

This section collected basic demographic data, including the respondents' roles in the construction industry, years of experience, and their involvement in high-rise building projects. This information was crucial for understanding the background of the respondents and ensuring that the sample represented a cross-section of relevant professionals.

- **Section B: Knowledge and Experience with Compartmentalization**

This section focused on the respondents' familiarity with compartmentalization techniques, their application in high-rise buildings, and their perceived effectiveness in fire protection. Questions were designed to assess both the theoretical knowledge and practical experience of the respondents.

- **Section C: Benefits of Compartmentalization**

Respondents were asked to evaluate the benefits of compartmentalization, such as its impact on fire containment, occupant safety, and energy efficiency. This section employed Likert scale questions to quantify the respondents' agreement with various statements related to the benefits of compartmentalization.

- **Section D: Challenges and Recommendations**

The final section sought to identify any challenges encountered in implementing compartmentalization and to gather recommendations for improving its effectiveness in South African high-rise buildings. This section included open-ended questions, allowing respondents to provide detailed feedback and suggestions.

3.3 Types of Questions

The questionnaire included a mix of closed-ended and open-ended questions:

- **Closed-Ended Questions**

These included multiple-choice questions and Likert scale questions. Multiple-choice questions were used primarily in Sections A and B to gather specific information about the respondents' demographics and knowledge. Likert scale questions were used in Sections C and D to measure the degree of agreement or disagreement with statements regarding the benefits and challenges of compartmentalization.

- **Open-Ended Questions**

Open-ended questions were included in Section D to allow respondents to elaborate on their experiences, challenges, and recommendations related to compartmentalization. These questions provided qualitative insights that complemented the quantitative data collected through the closed-ended questions.

3.4 Data Collection and Analysis

A total of 120 questionnaires were distributed to construction industry professionals in Johannesburg, South Africa. Both physical copies and digital versions (via Google Forms) were used to maximize response rates and accessibility. Of the 120 questionnaires distributed, 107 were completed and returned, resulting in a high response rate of 89%.

The collected data were analyzed using the Statistical Package for Social Science (SPSS). Descriptive analysis was conducted to summarize the demographic data and respondents' overall perceptions of compartmentalization. Factor analysis was employed to identify underlying patterns and relationships within the data. To ensure the reliability and validity of the questionnaire, Cronbach's Alpha was calculated, confirming that the questionnaire items had a high level of internal consistency.

4. Findings and discussion

The following graphs show the background information of the respondents, which includes their professional qualifications, highest level of education and years of experience in the construction industry.

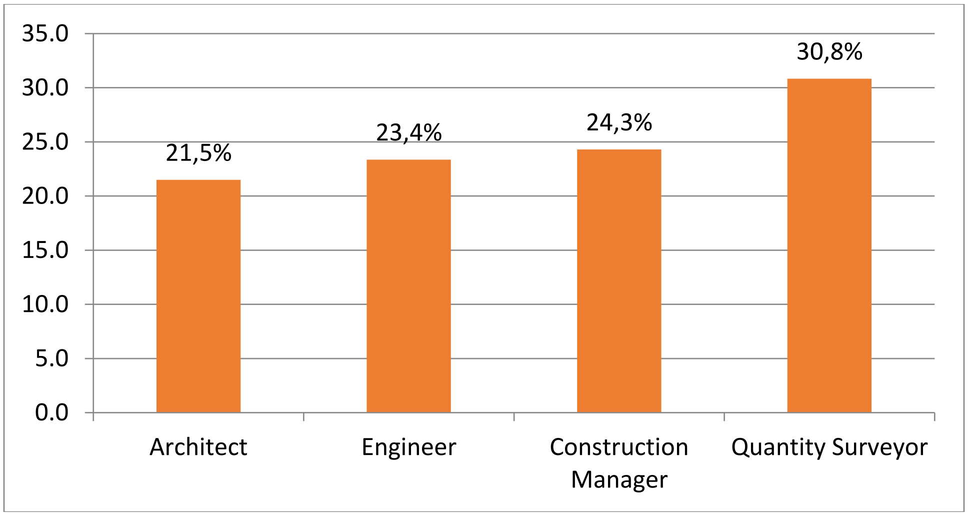

Fig. 1: Professional qualification distribution

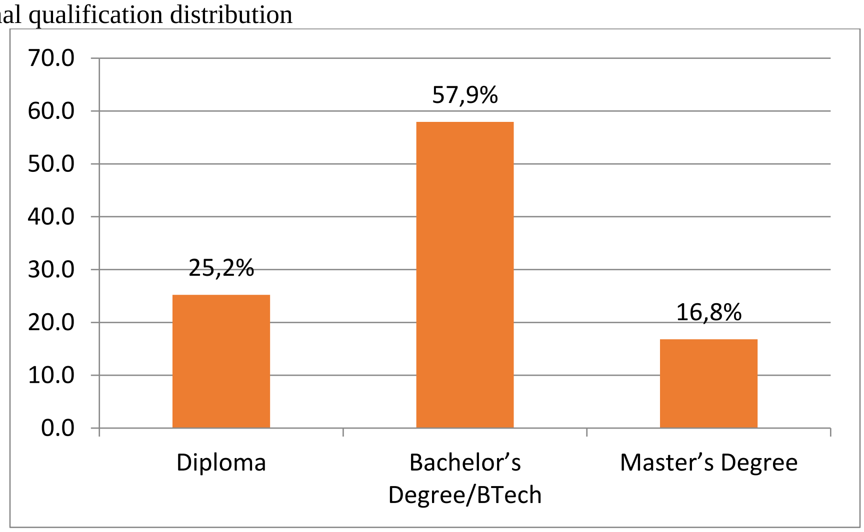

Fig. 2: Educational qualification

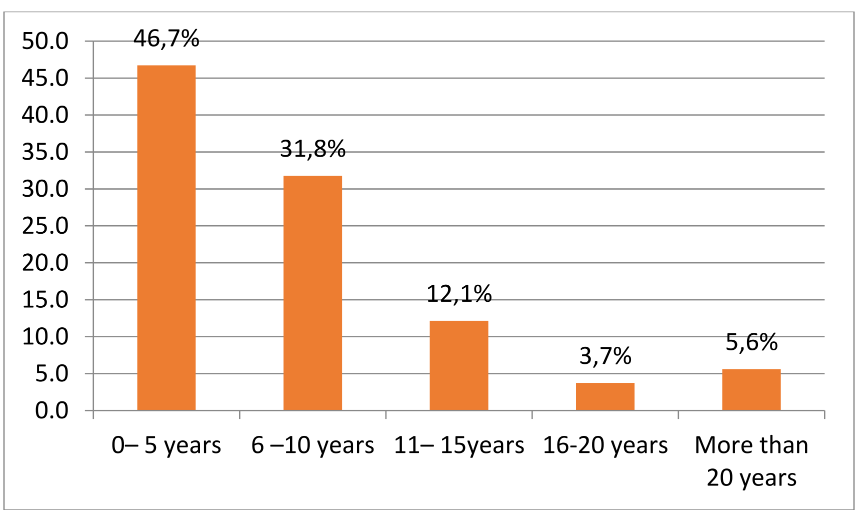

Fig. 3: Years of experience distribution

Descriptive analysis results

Benefits of compartmentalization were derived from the related literature. Respondents were requested to rate to what extent does each variable were a benefit of compartmentalization for fire safety using 5-point Likert scale from "No extent to Very large extent". Thirteen variables were listed as benefits, ten of were rated above average which is "moderate extent" on scale and the other three were below that. The most rated benefits included protection of escape routes; limits spread of fire that could trap occupants; extend time for fire fighters to extinguish with success; keeps fire in a place of origin, maximise evacuation time, minimise spread of fire to other buildings; controls smoke in the building and that it protects other parts of building from toxic smoke effects.
Descriptive results analysis with Mean Item Scores (MIS), standard deviation of variables and exploratory factor analysis results of the benefits are presented below. The table below shows the descriptive analysis results.

Table 1- Benefits of compartmentalization

Benefits of adopting compartmentalization	Mean	Standard deviation	Rank
Protects escape routes from fire	4.04	0.941	1
Limits rapid spread of fire that could trap occupants inside	3.97	0.936	2
Extend time for fire-fighters to extinguish with success	3.95	0.935	3
Keeps fire in the place of origin	3.92	1.056	4
Maximise evacuation time	3.91	1.042	5
Minimise spread of fire to other buildings	3.76	1.026	6
Controls smoke in the building	3.75	1.020	7
Protect other parts of the building from toxic smoke effects	3.65	1.038	8
Avoid structural collapse	3.49	1.127	9
Addresses stack effect problems	3.19	1.158	10
Enhances occupants' comfort	2.83	1.240	11
Ensures capital saving	2.73	1.225	12
Ensures energy saving	2.59	1.205	13

Correlation matrix

Correlation matrix shows the strength of relationship between two factors. The suitability of data was done prior the performance of Principal Component Analysis. Correlation matrix results shows presence of coefficient that is above 0.3 which confirms factorability of the data.

Table 2: Correlation matrix

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13
F1	1.000	0.744	0.661	0.645	0.585	0.637	0.284	0.415	0.442	0.472	0.247	0.345	0.135
F2	0.744	1.000	0.773	0.752	0.728	0.783	0.361	0.490	0.537	0.574	0.155	0.314	0.115
F3	0.661	0.773	1.000	0.741	0.644	0.674	0.338	0.497	0.481	0.485	0.232	0.319	0.157
F4	0.645	0.752	0.741	1.000	0.700	0.731	0.294	0.469	0.528	0.488	0.209	0.304	0.170
F5	0.585	0.728	0.644	0.700	1.000	0.763	0.421	0.444	0.572	0.594	0.322	0.336	0.247
F6	0.637	0.783	0.674	0.731	0.763	1.000	0.378	0.505	0.641	0.640	0.182	0.292	0.166
F7	0.284	0.361	0.338	0.294	0.421	0.378	1.000	0.484	0.524	0.387	0.698	0.436	0.715
F8	0.415	0.490	0.497	0.469	0.444	0.505	0.484	1.000	0.502	0.475	0.475	0.435	0.342
F9	0.442	0.537	0.481	0.528	0.572	0.641	0.524	0.502	1.000	0.646	0.376	0.308	0.390
F10	0.472	0.574	0.485	0.488	0.594	0.640	0.387	0.475	0.646	1.000	0.293	0.368	0.304
F11	0.247	0.155	0.232	0.209	0.322	0.182	0.698	0.475	0.376	0.293	1.000	0.562	0.799
F12	0.345	0.314	0.319	0.304	0.336	0.292	0.436	0.435	0.308	0.368	0.562	1.000	0.574
F13	0.135	0.115	0.157	0.170	0.247	0.166	0.715	0.342	0.390	0.304	0.799	0.574	1.000

Kaiser-Meyer-Olkin (KMO)
Table 3 presents Kaiser-Meyer-Olkin (KMO) and Barlett's test of sphericity. This is done to address concerns with of factorability and strength of the inter-correlations among the variables (Pallant, 2007). The table below presents the results of the KMO with the data returning a value sampling adequacy of 0.899 and the significance value of 0.000. This is considered sufficient to conduct a factor analysis.

Table 3: KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		0.899
Bartlett's Test of Sphericity	Approx. Chi-Square	999.092
	Df	78
	Sig.	0.000

Total variance explained.
The rotation method used for the data was Varimax rotation. The eigenvalue was at conventional high values of 1.0. Table 4 shows the grouping of benefits of compartmentalization for fire safety in high-rise buildings and their eigen-values. Two groups of compartmentalization benefits with eigen values exceeding 1 were retained, resulting in 6.690 and 2.283 which explains 51.462 percent and 17.564 percent of the variance. These two factors accumulated 64.291 percent of total cumulative variance which shows their importance from the other benefits.

Table 4: Total variance explained

Factor	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	**6.690**	51.462	51.462	6.339	48.765	48.765	5.229	40.225	40.225
2	**2.283**	17.564	**69.026**	2.018	15.526	64.291	3.129	24.067	**64.291**
3	0.786	6.047	75.073						
4	0.594	4.572	79.645						
5	0.565	4.343	83.988						
6	0.401	3.087	87.076						
7	0.347	2.667	89.743						
8	0.313	2.410	92.152						
9	0.307	2.365	94.518						
10	0.236	1.818	96.336						
11	0.186	1.429	97.765						
12	0.156	1.204	98.969						
13	0.134	1.031	100.000						

Scree plot
An inspection of the scree plot on Figure 1 shows the break after the second factor. The steep slope shows the factors with eigen value that is above 1, while the horizontal line shows the rest of the factors that have an eigen value lower.

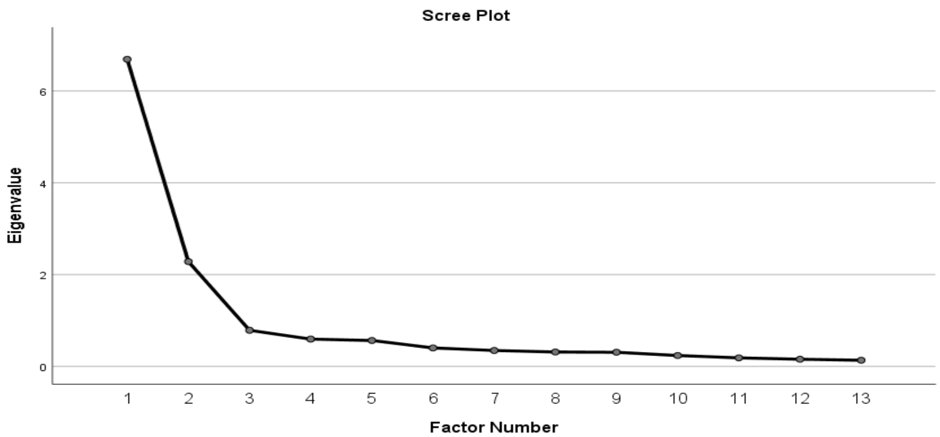

Fig. 1: Scree plot

Rotated factor matrix

Principal Axis Factoring showed two factors with eigen value above 1.0. The factors were named based on the relationship they have under each factor. Factor 1 was named **Protection of lives** and Factor two, **Sustainability.**

Table 5: Rotated factor matrix

Factor		
	1	2
F2	**0.909**	0.095
F6	**0.873**	0.152
F4	**0.825**	0.130
F3	**0.802**	0.150
F5	**0.782**	0.251
F1	**0.740**	0.143
F10	**0.624**	0.318
F9	**0.597**	0.405
F8	**0.501**	0.442
F13	0.026	**0.913**
F11	0.098	**0.886**
F7	0.283	**0.750**
F12	0.270	**0.576**

Factor 1- Protection of lives

Nine compartmentalization benefits were extracted for factor one, which included, Keeps fire in the place of origin (74%); Protects escape routes from fire (90.9%); Maximise evacuation time (80.2%); Extend time for fire-fighters to extinguish with success (82.5%); Controls smoke in the building (78.2%); Limits rapid spread of fire that could trap occupants inside (87.3%) and protects other parts of the building from toxic smoke effects (62.4%). This factor accounted to 51.462% of the variance.

These criteria share a common link to protection of live, agreeing with Mauritius Fire Code (2018: 79), who mentioned that to minimise the risk of spread of fire between adjoining buildings, prevention of untimely collapse of the building in the event of fire, stable and durable form of construction is provided to prevent spread of fire by dividing building into compartments. Sturgeon (2017:5A-1), stated that fire compartments are constructed to keep fire in place of origin, limits damages on building fabric and limiting exposure of occupants and adjacent buildings to injury because of fire.

Factor 2- Sustainability

The four benefits were extracted for factor 2, which included Enhances occupants' comfort (75.0%); Ensures energy saving (88.6%); Addresses stack effect problems (57.6%) and ensures capital saving (91.3%). This factor accounted to 17.564% of variance.

These criteria share a common link to sustainability. Opoku & Ahmed (2015:16) said that sustainable thinking from the design stage is of importance in the building as it could save cost or reduce costs in future. Passive and active fire safety systems can be installed in a building to reduce maximum loss. United Arab Emirates code (UAE) (2011:29) mentioned that maintaining the highest level of building users' safety, be it physical, mental, or social can provide consistency and reliability needed to grow business or building community.

5. Conclusions

In conclusion, this study underscores the critical importance of compartmentalization as a passive fire safety measure in high-rise buildings. The findings reveal that compartmentalization significantly enhances fire protection by safeguarding escape routes, containing the spread of fire, extending the time for firefighters to manage incidents, and maximizing evacuation time, all of which contribute to protecting lives, property, and the environment. Additionally, the practical applications of these benefits emphasize the necessity of integrating compartmentalization into modern construction practices to ensure comprehensive safety in urban developments. The results advocate for the widespread adoption of compartmentalization strategies to bolster fire safety protocols and resilience in high-rise structures.

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