

Performance-Based Fire Safety Assessment and Optimization of a Mixed-Use High-Rise Building Using NBC 2016, Hydraulic Adequacy, and Evacuation Time Analysis

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Abstract

This paper presents a performance-based fire safety assessment of a simulated 92 m mixed-use high-rise building containing parking, commercial, office, and residential occupancies. Rather than relying only on prescriptive compliance, the study evaluates whether the installed fire protection strategy can maintain tenable conditions and deliver adequate suppression performance during a credible design fire. Using the base data supplied for the Metro Central Tower case, the work determines fire load density, selects a retail floor design fire, checks flashover development, verifies hydrant and sprinkler pressure availability at the most remote level, and compares Available Safe Egress Time (ASET) against Required Safe Egress Time (RSET). A staircase flow model is then used to examine full-building evacuation performance under peak population, and a weighted Fire Safety Index (FSI) is applied to compare pre- and post-optimization system performance. The base case indicates that the building may satisfy installation intent but still fails key performance objectives at upper levels: the top-floor hydraulic condition is deficient, the ASET-RSET margin is critically small on shopping floors, and total evacuation time exceeds the tenable window. The optimized case, incorporating pressure zoning, a high-head fire pump, improved alarm/voice communication, smoke exhaust, and additional exit capacity, significantly improves suppression reliability and life safety margin. The manuscript contributes an integrated, code-linked framework for industrial safety engineering practice by combining Indian code context, hydraulic screening, tenability analysis, and evacuation assessment in a single mixed-use high-rise case study.

Keywords: Fire safety engineering, mixed-use high-rise building, NBC 2016, hydraulic adequacy, ASET, RSET, evacuation modelling, Fire Safety Index

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INTRODUCTION

Rapid urbanization in Indian metropolitan regions has accelerated the construction of vertically stacked buildings that combine shopping areas, offices, apartments, services, and parking within a single envelope. These mixed-use high-rise buildings concentrate diverse fuel loads and human behaviors into one vertical system, making the fire problem fundamentally different from that of a single-occupancy building. Although the prescriptive provisions in the NBC 2016 and allied Indian and international standards remain essential minimum requirements, contemporary fire engineering practice increasingly recognizes that code compliance alone does not necessarily prove survivability under a realistic fire scenario [1–10].

The uploaded source manuscript already identified the essential engineering problem: a 92 m hypothetical tower may appear compliant at the installation stage, yet upper-floor suppression pressure, smoke tenability, and evacuation flow can still become inadequate under peak occupancies and design fire conditions. In high-rise fires, internal fire protection systems, such as pumps, risers, sprinklers, alarms, smoke control systems, and protected stairs, become the principal life safety infrastructure because external firefighting intervention is limited by height, access, smoke spread, and time [1, 5–9].

Therefore, performance-based fire safety engineering is well-suited for mixed-use towers. This enables the designer to define design fires, quantify system responses, and compare tenability with occupant responses using engineering calculations or simulations. Foundational fire engineering texts and standards emphasize that a credible design must address fire growth, smoke movement, detector/alarm response, occupant pre-movement behavior, egress flow, and system reliability as an integrated whole [10–18].

This study reformulates the user-provided case study as a structured research manuscript. This study makes three contributions. First, it converts the original technical note into a journal-style paper with clearer research framing, methodology, and interpretation. Second, it supplements the initial calculations with a more systematic literature review and an explicit literature gap for mixed-use Indian high-rise buildings. Third, it offers an integrated assessment workflow that can be adapted by industrial safety engineers, fire consultants, and academic researchers for the early-stage screening of tall building fire safety.

LITERATURE REVIEW AND LITERATURE GAP

Fire safety research for tall buildings has evolved from prescriptive design support to integrated performance-based assessment. Early life safety work by Cooper established the ASET concept, creating a quantitative basis for comparing the available tenable time to the evacuation needs [16]. Later work by Averill et al. refined the RSET by highlighting the uncertainty in the detection, notification, pre-movement, and travel components [17]. These ideas remain central to performance-based design and are embedded in modern risk-based practices [15, 18].

High-rise evacuation studies have shown that building use, occupant familiarity, disability, phased evacuation strategies, and vertical circulation geometry strongly affect the total evacuation time. The review and case study work by Ronchi and Nilsson, Kuligowski and Hoskins, Oven and Cakici, Hassanain, Koo et al., and Rismanian and Zarghami collectively show that pre-movement delay, stair capacity, and behavioral diversity are often as important as nominal exit width [18–21, 22–24].

Parallel research on smoke control and system integration demonstrates that tall building safety depends not only on egress but also on smoke extraction, stair pressurization, and suppression reliability. Alianto et al. reviewed the importance of smoke movement control and argued that performance-based approaches are required when the geometry and operational objectives are too complex for a purely prescriptive design [25]. Recent studies using CFAST, PyroSim, Pathfinder, and machine-learning-assisted optimization have further shown that the ASET-RSET framework can be strengthened by efficient scenario comparison and digital analysis [26–29].

Despite this progress, an important gap remains in the Indian context. Many published studies focus on single-occupancy towers, simulation benchmarking, or international codes, whereas relatively few integrate NBC/BIS requirements, hydraulic adequacy, design fire screening, smoke tenability, and evacuation capacity in a mixed-use high-rise framework. Furthermore, practical screening studies often stop at code-checking and do not explicitly connect pump pressure, riser losses, ASET/RSET, and whole-building evacuation in a single decision-support methodology. The present study addresses this gap by linking the Indian code context with a compact performance-based workflow suitable for academic analysis and preliminary engineering review, as shown in Table 1.

Area of Study and Building Description

The study area was a simulated urban mixed-use high-rise building named Metro Central Tower. The source data represent a hypothetical Indian metropolitan building intended for research and pedagogical analysis rather than for the forensic evaluation of an existing structure. This distinction is important because the calculations are best interpreted as screening-level fire engineering checks that demonstrate the methodology and risk trends (Table 2) [1, 2, 10].

PROBLEM IDENTIFICATION AND PROBLEM FORMULATION

The base manuscript identified four interrelated fire safety concerns. First, the building height imposes a substantial static head burden on the standpipe and sprinkler systems. Second, commercial floors contain the most severe credible fuel packages and therefore dominate early smoke generation and flashover risk. Third, the occupant density on shopping floors and cumulative demand on stairs produce a narrow life safety margin if evacuation starts late. Fourth, the apparent presence of installed systems may create a false sense of security when the actual performance has not been verified under the design conditions.

Accordingly, the research problem is formulated as follows: can a 92 m mixed-use high-rise building designed to satisfy conventional installation intent also satisfy performance-based fire safety objectives when evaluated for suppression pressure, smoke tenability, and occupant egress under a credible design fire? If not, which engineering interventions provide the greatest improvement in the safety margin?

The specific study objectives are as follows: (i) estimate fire load density and fire growth characteristics for the governing fire compartment; (ii) verify hydraulic adequacy at the most remote hydrant and sprinkler point; (iii) compare ASET and RSET for occupant life safety; (iv) check staircase flow adequacy for full-building evacuation; and (v) quantify the effect of optimization measures using a weighted Fire Safety Index (FSI). These objectives are consistent with the performance-based design logic described in codes, standards, and fire engineering literature [1, 5–10, 15–18].

Table 1. Details of studies.

Ref.	Study	Main contribution	Limitation	Relevance to present work
[16]	Cooper (1983)	Defined ASET as a life safety measure based on the onset of untenable conditions.	Conceptual focus; not tailored to mixed-use tall buildings.	Provides a tenability basis for ASET comparison.
[17]	Averill et al. (2008)	Structured RSET components and highlighted modelling uncertainty.	Does not address hydraulic performance.	Supports evacuation time decomposition used here.
[18]	Ronchi and Nilsson (2013)	Comprehensive review of high-rise behavior and evacuation modelling.	Primarily review-oriented.	Supports literature gap and behavioral interpretation.
[19]	Kuligowski and Hoskins (2010)	Showed the importance of pre-movement delay in a real office fire.	Single event and office focused.	Justifies explicit reaction-time treatment.
[25]	Alianto et al. (2022)	Reviewed smoke control, stair pressurization, and performance-based tall building design.	The review does not provide an Indian code workflow.	Supports smoke management discussion and future scope.
[27]	Zhou et al. (2023)	Used simulation and machine learning to optimize high-rise egress.	Teaching-building focus.	Supports the optimization philosophy used in this paper.
[26]	Jang and Hwang (2024)	Demonstrated ASET estimation using CFAST for performance-based design.	Simulation-specific; not a hydraulic study.	Supports future CFD/zone-model extension.
[29]	Abu Dabous et al. (2024)	Mapped in recent research trends in high-rise fire prevention and mitigation.	Bibliometric rather than case analytical.	Shows current research direction and unresolved integration needs.

Table 2. Building description.

Parameter	Value	
Building type	Mixed-use high-rise building	
Overall height	92 m	
Floor configuration	2 basements + ground + 23 upper floors	
Total floor count	26 levels	
Floor plate area	1,200 m² per floor	
Total built-up area	31,200 m²	
Structural system	RCC framed structure	
Urban context	Metro-city fire load environment	
Occupancy mix	Parking, electrical/service, retail mall, offices, residential apartments	
Total building population	Approx. 2,740 persons under peak condition	
Stair configuration (base case)	Two fire stairs, each 1.5 m clear width	
Floor range	Occupancy	Design population density/basis
Basement 2	Car parking	1 person/100 m²
Basement 1	Parking + electrical rooms	1 person/80 m²
Ground to 3rd	Shopping mall/retail	1 person/3 m²
4th to 8th	Offices	1 person/10 m²
9th to 23rd	Residential apartments	4 persons/flat

Table 3. Methodology.

Step	Analytical task	Primary output
1	Select governing fire compartment	Retail/mall floor as most severe credible fire scenario
2	Estimate fire load density	Compartment fuel severity and hazard classification
3	Model design fire growth	Heat release rate and approximate flashover time
4	Check hydrant/sprinkler hydraulics	Residual pressure at most remote level
5	Estimate smoke tenability	ASET based on smoke layer descent / untenable conditions
6	Estimate evacuation demand	RSET and total stair discharge time
7	Apply engineering improvements	Optimized performance scenario
8	Compute Fire Safety Index	Comparative risk score before and after intervention

METHODOLOGY

The methodology adopted in this study follows a sequential performance-based screening workflow. The design fire compartment was selected, the fuel load was estimated, the flashover timing was checked, the firefighting water supply was hydraulically evaluated, the smoke tenability was assessed using an ASET-RSET comparison, the whole-building evacuation flow was estimated, and the effect of optimization measures was quantified. The workflow intentionally combines simple analytical calculations with code-linked assumptions to ensure transparency and reproducibility for academic and early design applications (Table 3) [1–4, 10–18].

Governing Design Fire

Because commercial floors combine high combustible load density, open floor layout, rapid public occupancy growth, and strong smoke production potential, the shopping level was adopted as the governing fire compartment. This choice is consistent with both the source manuscript and the broader literature, which often identifies mercantile floors as dominant tenability drivers in mixed-use towers [1, 2, 10, 16, 18].

A medium-growth t^2 fire is assumed: $Q = \alpha t^2$, where Q is the heat release rate (kW), $\alpha = 0.012$ kW/s² for a medium-growth retail fire, and t is the time in seconds. The flashover criterion was approximated to be 1 MW for screening purposes. The time to flashover is therefore $t = \sqrt{1000 / 0.012} \approx 288.7$ s, or approximately 4.8 min. This value is not a substitute for compartment fire simulation but provides a practical benchmark for comparing the suppression response and tenability window.

Fire Load Density and Hazard Interpretation

The uploaded case data state that the retail floor contains plastic goods, textiles, packaging cartons, and furniture, leading to a calculated fire load density of 872 MJ/m². For preliminary design interpretation, the compartment is treated as equivalent to an ordinary hazard retail condition, requiring robust sprinkler coverage and early suppression reliability [2, 5, 10, 11].

Hydraulic Adequacy Assessment

Hydraulic adequacy is checked at the most remote upper-floor point because tall buildings commonly fail at this location. The screening relationships used are $P_{\text{static}} = 0.1 \times H$ (bar), $P_{\text{av}} = P_{\text{pump}} - P_{\text{static}} - P_f$, and performance acceptance when the top hydrant residual pressure is at least 3.5 bar and the sprinkler residual pressure is at least 1.0 bar. Using $H = 92$ m, $P_{\text{pump}} = 8.5$ bar, and friction loss $P_f = 2.5$ bar, the available pressure becomes $P_{\text{av}} = 8.5 - 9.2 - 2.5 = -3.2$ bar. The results indicate that the top system is hydraulically inadequate and that the base pump head is insufficient for reliable upper-floor standpipe and sprinkler operation.

ASET-RSET Framework

The tenability check compares the ASET with the RSET. The ASET is the interval between fire detection and the onset of untenable conditions for occupants, whereas the RSET is the time required for occupants to detect, understand, react, and move to safety [16, 17, 26]. The source case used a smoke-filling approximation for a 4.2 m high retail floor and obtained an ASET of approximately 230 s (3.8 min) for the descent of the smoke layer to a critical level. The RSET is decomposed into detector activation (45 s), alarm transmission (20 s), pre-movement/human reaction (120 s), and travel time to the stairs (37 s), giving $RSET = 222$ s (3.7 min).

Evacuation Capacity Analysis

The staircase flow capacity was screened using $\text{flow} = 1.3 \times \text{width}$ persons/s for each stair. With two stairs of 1.5 m each, the per-stair flow was 1.95 persons/s, and the total flow was 3.9 persons/s. For a total population of 2,740 persons, the evacuation discharge time is approximately $2740/3.9 = 702$ s (11.7 min). This result is intentionally conservative because it treats the building population as a system-level evacuation demand; however, it is appropriate for identifying whether the stair arrangement is under-capacitated relative to the available tenability.

Optimization Logic

The improvement strategy follows a risk-reduction hierarchy: (i) improve suppression reliability by increasing the pump head and introducing pressure zoning; (ii) improve occupant notification and reduce pre-movement through voice alarm and training; (iii) improve ASET using mechanical smoke exhaust; and (iv) improve evacuation throughput by adding a third fire staircase and supporting smoke-lobby/fire-door control measures. Therefore, the revised scenario combines active and passive measures rather than relying on any single intervention.

Fire Safety Index

To compare the system performance before and after optimization, a weighted semiquantitative FSI was retained from the source manuscript. Detection, suppression, smoke control, evacuation, and reliability were weighted 20, 25, 20, 20, and 15, respectively. The FSI is used as a comparative decision-support measure rather than as a universal regulatory metric. Its main value lies in showing whether the combined system moves from an unacceptable to an acceptable performance band after an engineering intervention.

RESULTS AND ANALYSIS

The result set clearly demonstrates the necessity of performance-based verification for high-rise buildings. In the base case, the upper-floor water delivery problem was severe enough to undermine both hydrant operations and sprinkler effectiveness. Because the calculated available pressure is negative, the system would not merely be marginal; it would fail to satisfy the fundamental objective of delivering the required residual pressure at the most remote point of the system. This finding aligns with field and case-based observations reported in the high-rise fire engineering literature, where inadequate pressure and poor system integration often remain hidden until the most demanding scenario is examined (Table 4) [5, 6, 25, 30, 31].

The tenability comparison is equally important in this regard. The base case ASET of 3.8 min and RSET of 3.7 min leave only a 6 s margin. In practice, such a margin is not acceptable because of the uncertainty in the detector response, occupant recognition, public behavior, congestion, smoke stratification, and door operation. The literature consistently shows that occupant pre-movement delays can vary significantly depending on cues, familiarity, management, and the perceived seriousness of the event [17–20]. Therefore, the base case should be interpreted as effectively unsafe, even though the ASET is nominally greater than the RSET.

The whole-building evacuation check reinforces this conclusion. An estimated 11.7 min to discharge 2,740 occupants through two 1.5 m stairs is far longer than the tenable window available in the governing retail scenario. This means that even if initial movers can begin egress, the downstream stair capacity becomes a bottleneck for overall life safety. This finding is consistent with high-rise evacuation studies that identify stair capacity, population characteristics, and management strategy as the dominant determinants of actual evacuation performance [18, 20, 27, 22–32].

The optimized case shows that targeted interventions can change performance. Increasing the pump head to 16 bar and introducing pressure zoning lifted the top-floor available pressure to 4.3 bar, satisfying both hydrant and sprinkler screening criteria. Smoke exhaust increased the ASET to 7.5 min, whereas voice evacuation, improved messaging, and training reduced the RSET to 2.7 min. The safety margin increases from seconds to minutes, converting a near-failure condition into a more resilient life safety outcome. The addition of a third staircase further reduces the full-building evacuation time to 7.8 min; although still substantial, it becomes compatible with the improved tenability conditions and supports staged, managed evacuation. The FSI improvement from 52 to 87 confirms the value of integrated optimization rather than a single-parameter correction.

Table 4. Results and analysis.

Parameter	Base case	Optimized case	Interpretation
Top-floor available hydraulic pressure	-3.2 bar	4.3 bar	Base case fails to deliver water effectively; optimized case restores usable residual pressure.
Hydrant adequacy criterion	Fails (required ≥ 3.5 bar)	Passes	Hydrant system becomes functional only after high-head pumping/zoning.
Sprinkler adequacy criterion	Fails (available < 1.0 bar)	Passes	Upper-floor sprinkler operation is unreliable before intervention.
Flashover time in governing compartment	Approx. 4.8 min	Approx. 4.8 min	Fire severity unchanged; optimization acts on response, not fuel package.
ASET	3.8 min	7.5 min	Smoke exhaust substantially improves the tenability window.
RSET	3.7 min	2.7 min	Voice alarm/training reduces pre-movement delay.
ASET-RSET safety margin	0.1 min (6 s)	4.8 min	Base case is critical; optimized case is robustly survivable.
Whole-building evacuation time	11.7 min	7.8 min	Additional stairs improve discharge capacity, but the system remains sensitive to management quality.
Fire Safety Index	52 / 100	87 / 100	Performance moves from unsafe to acceptable band.

DISCUSSION

The most important implication of this study is that prescriptive compliance and actual performance are not the same. A designer may install hydrants, sprinklers, and alarms in nominal accordance with a code checklist; however, the combined system can still fail when vertical pressure loss, congestion, smoke spread, and human delay are considered together. For industrial safety engineering, this finding is significant because it shifts attention from component presence to functional adequacy under scenario-based demands.

The second implication is methodology. The integrated workflow used here is intentionally simple enough for teaching, preliminary audit, and concept design, but rich enough to reveal major deficiencies in the process. It can be applied early in the design process, before detailed CFD or evacuation software is commissioned. This makes it particularly valuable for academic institutions, consulting offices, and authorities reviewing conceptual mixed-use towers in rapidly growing urban contexts.

At the same time, the study has limitations. The building is hypothetical; the friction loss is represented by an engineering approximation; the ASET calculation is screening-level rather than CFD-based; the evacuation calculation does not include phased evacuation, mobility impairment distributions, or dynamic occupant routing; and the FSI is a semiquantitative comparison tool rather than a regulatory acceptance method. These limitations do not invalidate the conclusions; rather, they define the level of inference of the study. Therefore, this study should be understood as a robust preliminary performance assessment and not as a substitute for full code approval documentation, hydraulic network calculation, or detailed simulation model validation [15, 26, 30–33].

CONCLUSION

This study converted the supplied technical note into a structured performance-based fire safety manuscript for a simulated 92 m mixed-use high-rise building. The analysis established that the governing retail fire scenario is the controlling life safety case because it combines high fire load, rapid smoke generation, and dense occupant presence. The base case hydraulic assessment showed that the installed 8.5 bar pump head was insufficient for upper-floor hydrant and sprinkler reliability, producing an available pressure of -3.2 bar at the most remote level. The tenability analysis indicated an ASET of 3.8 min versus an RSET of 3.7 min, leaving only a negligible survival margin, whereas the whole-building evacuation demand required 11.7 min through two 1.5 m stairs.

Engineering optimization decisively changed the safety outcomes. A 16-bar high-head pump with pressure zoning restored the residual pressure, smoke exhaust increased the ASET, alarms and training measures reduced the RSET, and an additional staircase improved the evacuation capacity. The net effect was an increase in the FSI from 52 to 87. Therefore, this study confirms that mixed-use high-rise fire safety should be evaluated as an integrated system problem. In practical terms, although code provisions remain necessary, performance-based verification is essential to demonstrate that a building can protect occupants during a credible fire event.

Future Scope

Future work should extend this framework in five directions: First, CFD- or zone-model-based smoke calculations should be used to replace the screening smoke-filling approximation and quantify the temperature, visibility, and toxic species in the breathing zone. Second, hydraulic network modelling should include pipe topology, simultaneous demand, hose-stream allowance, and pump curve verification. Third, evacuation analysis should consider phased evacuation, mixed-ability populations, lift-assisted egress (where permitted), and human behavioral uncertainty. Fourth, the semiquantitative Fire Safety Index can be improved through expert weighting, sensitivity analysis, and probabilistic reliability treatment. Finally, the framework should be validated for real Indian high-rise buildings using field data, drill observations, and digital twin/BIM-enabled fire safety management.

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