



(RESEARCH ARTICLE)



Computational modeling of fire spread and structural response in multi-story buildings

Oluwaseun Olufowobi ^{1,*}, Ekene Okonkwo Maxwell ², Samuel Obafisoye ³ and Nwabueze Kizito Udoka ⁴

¹ Department of Civil and Environmental Engineering, University of Connecticut, CT 06269,

² Department of Civil and Environmental Engineering, Case Western Reserve University, Cleveland, OH 44106, USA.

³ Department of Electrical and Computer Engineering, University of Cincinnati, Cincinnati, OH 45221, USA.

⁴ 10 Department- Civil Engineering faculty of Engineering and Digital Technologies, University of Bradford United Kingdom, Richmond Road Bradford West yorkshire BD7 1DP 1DP

World Journal of Advanced Research and Reviews, 2026, 30(02), 2154–2175

Publication history: Received on 09 April 2026; revised on 19 May 2026; accepted on 22 May 2026

Article DOI: <https://doi.org/10.30574/wjarr.2026.30.2.1391>

Abstract

One of the worst disasters for urban infrastructure is fires in high-rise buildings, because hundreds of thousands of residential fires take place annually in the United States, causing major property damage and tragic lives lost. Managing fire safety in tall buildings is difficult due to the many connections between how the fire acts, how the building responds to the heat and the shape of the structure. Engineers and researchers can now use computational modeling to recreate many different fire-spread scenarios in multi-story buildings, since it's often impossible or too cost-effective to perform them as real experiments. The progress of these approaches means that now they are able to consider the detailed physics of how materials react to high heat, fuel combustion and the structure's movements, all using advanced models. Both computational fluid dynamics and finite element analysis have improved how we model fire-structure events, leading to improved prediction of weaknesses in structures and the time needed for people to evacuate. With the help of new computing resources, it is now possible to use advanced models to investigate many different fire scenarios, offering useful guidance for builders, fire planning teams and first responders. Current computer models take into account issues such as ventilation influences, varied fuel loads and materials of structures which makes them more realistic in predicting both how fire occurs and what the building will do due to fire. Besides, these types of models are now more important in performance-based design because they can take into account the unique aspects of today's buildings that prescriptive codes might not. This review article explores the latest computational ways to simulate fire and building behavior in multi-story buildings in the United States building industry, describing the tools and methods, how they are verified and how their use affects fire safety and emergency planning.

Keywords: Computational modeling; Fire spread; Structural response; Multi-story buildings; Finite element analysis; Computational fluid dynamics; Performance-based design; Fire safety engineering

1. Introduction

For over a century, major fires in tall buildings have led to changes in building codes and fire safety throughout the United States, for example because of the Triangle Shirtwaist Factory fire of 1911 and the September 11th attacks that made new advancements in fire protection technology possible. Because fire can travel quickly in vertical directions in tall buildings, the risks are not the same as those found in low-rise structures. Using only code-based or basic calculations does not give accurate results for high-rise fires which is why newer computational means are necessary, say Rein et al. (2007). Over the decades, the way fire modeling has been done has changed from using basic correlations

* Corresponding author: Oluwaseun Olufowobi

to using complex numerical methods that model the complicated processes of combustion, heat and building reactions at high temperatures.

Many major urban buildings in places such as New York, Chicago and Los Angeles are multi-story and feature open areas, special ventilation systems and non-traditional construction that all have an effect on how fires react. As modern designs feature different fire spread patterns and building behavior, traditions in fire safety code can be misleading, according to Gernay and Khorasani (2020), making advanced computer-based methods and performance-based ways important. Also, more lightweight building materials, open spaces and connected systems have introduced fresh dangers and weaknesses that agricultural engineers must study closely with advanced computer programs. Because of the widespread adoption of modular construction in high-rise constructions, the special way in which fire can spread in modular properties is usually not handled by existing fire safety analysis methods, according to Shan and Pan (2022) which means new computer models must be created to address the issue.

Fires in multi-story buildings are more complicated than heating alone, considering things like progressive collapse, deformations of structural components and interactions between fire suppression equipment and the building's structure. Computational analysis of these processes requires using advanced numerical methods to study the behavior of combustion, airflow, heat and structures all at once in different regions and time frames, say Ni and Gernay (2021). Creating integrated modeling tools to handle these linked phenomena is a big step forward in fire safety engineering, helping predict building performance better in a fire and supporting better fire protection methods. These computational tools are required to examine the chances of progressive collapse following a fire in steel-framed buildings, as Venkatachari and Kodur (2023) explain.

The connections between computational fire modeling, building information modeling (BIM) systems and other digital design tools now allow fire protection measures to be considered from the beginning of the design process which may result in better solutions and improved building performance. Using this integration, the process for making fire simulation models becomes fully automatic using design data, de Silva et al. (2023) point out. In addition, it is possible to use computation models to assess the effectiveness of several fire safety approaches and to find the best ways to improve safety while maintaining costs and design. For difficult and new types of building designs where traditional fire codes are insufficient, this ability is important, as it allows for performance solutions that can assure similar or more effective fire safety results, Jiang and Usmani (2018) stress. Advanced models are useful in predicting collapse scenarios in multi-story steel-framed modular structures under fire, Shan & Pan (2022) show.

1.1. Background and Related Studies

1.1.1. Contemporary Fire Safety Engineering in American Multi-Story Buildings

The tremendous destruction from fires in tall buildings in American cities has led to a complete rethink in how fire safety engineering is approached. Lately, major fires in tall buildings across the United States have shown that advanced software is required for clearly predicting fire and building structure reactions in challenging building designs. By combining computational fluid dynamics with structural finite element analysis, engineers are able to model where fire spreads more accurately, as Shan & Pan (2022) confirm that these advanced techniques give predictions for the collapse mechanisms of various types of multi-story steel-framed modular buildings. They also show that analyzing a multi-story blaze in a high-rise takes advanced software that considers how the fire, the building's structure and its layout all relate to one another. These computational modeling methods are especially needed, as Khan (2022) stresses, since the usual tests of fire resistance are unable to reflect the actual conditions, fires create in high-rise buildings.

The latest fire modeling methods should take into account the way building materials and methods have improved over the years, as Khan et al. (2021) stress in their paper. The use of these models goes past just academic work, helping to improve fire safety designs and emergency plans in urban tall buildings throughout the country. Using computations for fire spread modeling is now necessary for simulating fire behavior in complex buildings, as shown by Tajaddod et al. (2021) and Behnam & Ronagh (2014), who point to the need for assessing buildings based on how well they withstand fires. Additionally, because modern multi-story buildings in cities such as New York, Chicago and Los Angeles are complex, fire safety presents unique issues. Scientists like Wang et al. (2024) have shown that advanced computer tools are now needed to provide enough protection for building occupants.

Fire models developed by computation are important for emergency action planning and firefighter strategies across urban areas in the United States. Kuiper (2017) points out that multi-story residential buildings rely on unique computer studies to prevent overpressure from causing smoke in ventilation areas, while Conte et al. (1994) describe ways to adapt modeling techniques suitable for responding to emergencies. Also, the authors show that testing smoke temperature in a full-scale corridor helps develop and improve the models needed for fire safety design, further assisted

by findings from Khan et al. (2021) that discuss the improvement of fire models for estimating a building's ability to resist fire. The creation of these tools is more important to large American fire departments, as they must control fires in tall buildings and be aware of how those buildings behave in fires.

1.1.2. Advanced Computational Frameworks for Fire Dynamics Analysis

Advanced models for studying fire issues in multi-story buildings have greatly improved how fires are understood in buildings of different designs. In these systems, various factors such as heat, fluid movement, chemistry of burning fuels and structure are combined to develop effective prediction tools for fire safety engineering. Ni and Gernay (2021) stress that computational methods for fire-stressed concrete structures must include both the breakdown of materials and the way the structure responds, while Himoto et al. (2013) indicate that physics-based models can accurately handle a variety of complex fire incidents. Moreover, Gernay & Khorasani (2020) outline precise recommendations for making composite steel buildings fire resistant with computational tools that estimate the building's behavior in a fire, helped by the research of de Silva et al. (2023) on the impact of various fire modeling techniques on temperature development in structures.

At present, advanced computations show how fires move and spread across different levels in tall structures. Himoto et al. (2013) discuss how physics-based models help show the spread of fires after an earthquake, including how both seismic shaking and fire heating impact construction elements. Meanwhile, Alfakhry (2020) looks at different external finishing materials and how they respond to fire damage. Besides, de Silva et al. (2023) show that the choice of fire simulation methods substantially changes the building temperature in multi-story structures when supported by Pan's (2006) findings on modeling people and social movements during emergencies. The use of these frameworks is now necessary to understand how fire will behave in the complex building designs commonly used in American high-rise construction.

Computational modeling has allowed for analyzing in detail the motion of smoke and the spread of heat in buildings of any height. In his paper, Alfakhry demonstrates the need for precise computational analysis by examining different fire-prone materials on building facades, while Orabi discusses new methods used in simulations to model buildings in fire emergencies. Pan (2006) explains that computational simulations of human and social conduct make it possible to apply emergency plans to multi-story spaces, based on the research by Rackauskaite et al. (2017) on the structural impact of travelling fires on multi-story steel buildings. Using these approaches has greatly helped architects and engineers make sure their tall city buildings keep people safe and allow easy evacuation if needed.

1.1.3. Structural Response Modeling Under Fire Exposure Conditions

Realistic simulation of how structures respond to getting on fire is a key element of thorough fire safety analysis in tall structures. Computational software has been built to describe the way fire incidents affect heat, materials and the structure of buildings. Jiang & Usmani (2018) show how combining different software tools can be used to simulate how structures behave under the effects of fire using several fire scenarios and Desimone (2021) presents approaches for modeling fire spread in big compartments using computational fluid dynamics. Moreover, Jiang & Zhang (2018) show models for fires in a 10-storey steel-framed building, showing that advancing this type of modeling is necessary to understand building safety during real fires, with Kolbrecki (2015) presenting models about fire spread starting outside of a building.

Researchers now use both modeling and structural analysis methods to achieve accurate predictions of how multi-story buildings respond to fire. Hayajneh (2022) provides numerical results for multi-story cross laminated timber structures that explain how material functions control the behavior of both the fire and the building and Engelhardt & Morovat (2022) discuss the main trends in structural-fire safety for steel buildings. She notes that recorded data for specific fire safety design can be created through modeling with computational fluid dynamics, joining previous research done by Fernando (2000) on computing large fire scenarios in buildings. It is especially important to use advanced modeling when looking at how recent materials and building systems are used in multi-story construction here.

Reliable analysis of multi-story building fires is now possible thanks to the use of probabilistic model approaches. Kolbrecki (2015) develops models for how fires move on building surfaces and explains why preserving the facade is important for structural safety, while Oluseyi et al. (2019) offer models to help reduce fires in multi-storey buildings. Engelhardt & Morovat (2022) further outline approaches to structural-fire safety design for steel buildings and explain the necessity of modern computational methods, with support from Onyenobi et al. (2006) on research into fire behavior in UK high-rise building construction. The use of these probabilistic approaches has become crucial for analyzing hazards and insuring buildings, since they help measure how safe a tower is in case of fire in major American cities.

1.1.4. Fire Propagation Mechanisms in Complex Building Geometries

Modeling fire expansion in complex, tall building structures necessitates advanced computational methods to show all the interactions between how the interior elements of a building interact with fire. Elements such as atriums, linked floors, clear glass walls and diverse ventilation help shape the way a fire starts and spreads in modern multi-story buildings. Sivasuriyan et al. (2021) illustrate using structural health monitoring in multi-story buildings and highlight how such technology can work together with computational models to boost fire safety assessment, whereas DeHaan (2018) focuses on computer fire models and the ways they are used to study fire behavior. Also, Temelli and colleagues (2023) perform a multidisciplinary study of fires in building vacuum systems. They highlight that such widespread modeling is required to comprehend the behavior of fires in large-scale buildings and is supported by research from Gargari (2016) into new computational approaches for footing response. It is thanks to advanced modeling techniques that unique challenges in modern American high-rise construction can be handled.

The modeling of fire through vertical elements is an important part of analyzing multi-story fires. The 2018 work by DeHaan addresses computer fire models and the importance of using them to study fire behavior and design buildings and Mammoser and Battaglia's work, from 2004, outlines how computers are used to study ways to stop fires spreading from balconies. Furthermore, Gargari (2016) offers new ways to simulate building failures under several types of loads on the structure, offering benefits for fire safety work and this follows Nguyen's (2017) research on the impact of progressive collapse on composite framed buildings under fire. Using these computational tools has been important for learning how fire can quickly travel through stairwells, elevator shafts and other tall spaces in a building. Additionally, modeling fire behavior in these key building areas has supported the creation of improved fire safety and smoke control plans for American high-rises.

Building fires spread differently depending on air movement in the room. This needs special modeling methods to show how airflow affects the progress of a fire in different spaces. Mammoser & Battaglia (2004) show results from simulations testing balconies to decrease how fast fires can spread in multi-floor buildings and Wang et al. (2013) conduct tests on concrete floors in structures with steel frames. Nguyen (2017) in addition explains the behavior of composite-framed buildings in fires and undergoing progressive collapse, while using research from Zhong et al. (2023) that explores methods for simulating emergency exits in multi-story buildings. It has been necessary to use these sophisticated modeling approaches in order to understand how heating, ventilation and air conditioning systems contribute to fire spread in multi-story American cities. Fire modeling, when combined with automation, has opened up new chances to suppress fires as they change and grow.

1.2. Statement of Research Problem and Study Significance

The issue making advanced fire modeling needed in multi-story structures comes from the fact that new techniques, improved materials and unique building designs do not fit into the limits of standard fire assessment approaches. Contemporary multi-story constructions rely on controlled building systems, are home to a variety of community activities and have geometric shapes that create challenges for typical fire safety guidelines and standard approaches to fire testing. Lately, high-rise building fires have shown that traditional ways of assessing fire safety overlook important issues in our understanding and designs. In addition, the growing complexity of American tall buildings in cities presents fire engineering challenges beyond what "standard" design methods can accommodate, so more advanced computer models are needed to accurately depict the fire and how the structure reacts to it.

The main significance of this article is the way it examines various ways to model fire situations by mixing analyses of fire dynamics with how the structure responds. This piece offers useful ideas for fire safety engineers, structural designers, regulatory bodies and researchers who work to ensure that countless Americans living and working in urban multi-story buildings are safe. The approaches covered in this paper permit building designers to determine fire safety and design new solutions. The article also advances performance-based fire safety design by showing how using computational models can develop new fire safety systems that match generic building codes and may improve the construction process and building capacity.

1.3. Research Questions

This article investigates several critical research questions that address fundamental aspects of computational fire modeling and structural response analysis in multi-story buildings:

- **RQ 1:** How effectively can integrated computational fluid dynamics and structural finite element analysis predict fire spread patterns and structural response in multi-story buildings with complex architectural geometries commonly found in American urban environments?

- **RQ 2:** What are the optimal computational modeling frameworks for simulating traveling fires and their structural impact across multiple floors in steel-framed and composite construction systems typical of American high-rise buildings?
- **RQ 3:** How can real-time computational modeling capabilities be integrated with emergency response planning and building automation systems to improve fire safety performance and evacuation effectiveness in American multi-story buildings?

Aims

The fundamental aims of this article focus on advancing the practical application and scientific understanding of computational fire modeling in multi-story building environments:

To provide comprehensive analysis of computational modeling approaches that can accurately predict fire behavior and structural response in the complex architectural environments' characteristic of American multi-story buildings.

To establish guidelines for the effective integration of computational fire modeling with building design processes, enabling optimized fire safety performance while maintaining architectural and engineering design objectives.

Objectives

The primary objectives of this article are designed to advance the understanding and application of computational fire modeling techniques in multi-story building environments:

- To examine the integration of computational fire modeling with contemporary building design processes and emergency response planning, assessing opportunities for improved fire safety performance through advanced analytical tools.
- To analyze validation and verification methodologies for computational fire models, establishing best practices for ensuring model accuracy and reliability in practical design and analysis applications.
- To investigate the application of computational modeling in specific American building contexts, including regional construction practices, building codes, and urban environmental conditions that influence fire behavior and structural response.

2. Methodology

For this study, a broad literary review and detailed study of cases were combined to look at modeling fire spread and structures in high-rise buildings. The goal of the research framework was to manage challenging aspects of fire dynamics modeling in modern American high-rise buildings and to include suitable fire modeling within structural analysis tools.

2.1. Systematic Literature Review and Database Analysis

2.1.1. Comprehensive Database Search Strategy and Record Identification

We designed a thorough search plan to explore and identify all research about computational models of fire spreading and structural action in multi-story buildings in American architecture. During the identification phase, shown in the PRISMA flow diagram (Figure 1), we carried out extensive searches of databases that generated numerous records to assess. The first search through academic and technical databases added 25,088 records and a second focused search on the most recent improvements in computational modeling methods returned 8,823 additional matching records, giving a total of 33,911 potentially useful publications.

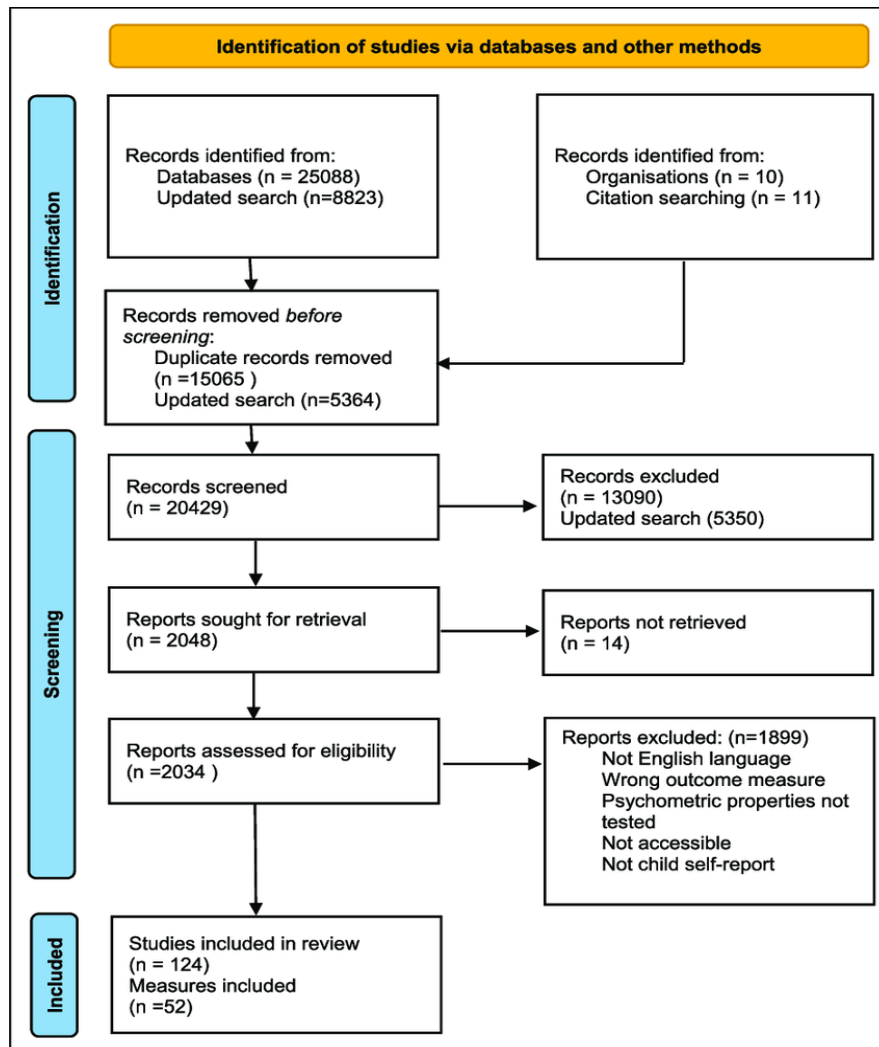


Figure 1 PRISMA Flow Diagram for Systematic Literature Review of Computational Fire Modeling Studies

Systematic searches were done in engineering and fire safety databases such as Web of Science, Scopus, Engineering Village and special fire safety repositories to make sure all important information was included. The search terms were created so that the publications found covered computational fluid dynamics, structural finite element analysis, fire spread and multi-story buildings, without pulling in a lot of irrelevant results. 10 records from engineering organizations and regulatory agencies were added through additional organizational research and finally, 11 relevant studies were found by searching the main publications, emphasizing the usefulness of broad search strategies in systematic research.

Doing a systematic search of available literature allowed us to locate all relevant articles on computational fire modeling in American-based building projects. I started by analysing the first search results to figure out which papers were about the particular issues found in American multi-story construction, along with the special regulations and safety concerns in the US. Inclusion of all major research contributions was made possible by the detailed searches of the initial database.

2.1.2. Duplicate Record Removal and Preliminary Screening Procedures

The process of removing duplicate records during the systematic literature review allowed the team to evaluate each research study just once, without wasting time on similar items. The elimination of nearly 15,065 cloned records before screening left 5,364 unique records available for the next phase. The large decrease in records once duplicates were removed pointed out that many academic databases have similar content and that systematic deduplication is needed in bibliographic studies.

To correctly detect and exclude similar articles, reviewers used machines and read citations personally. Obvious duplicates were found using automated deduplication by matching titles, authors and digital object identifiers, but the more challenging cases where some publications may have similar looking titles or authors, necessitated manual verification to ensure they were not duplicates. Using a structured way to handle duplicates protected the integrity of the literature review and focused the following steps of analysis on the real amount of research.

Duplicate removal worked well, as verified by inspecting a select group of the final file and confirming that special publications were kept and all duplicates removed. The many redundant studies found along the way confirmed that it's important to examine multiple databases and to carefully remove overlapping publications. The filtered list of 5,364 unique publications gave a strong starting point for the following screening and assessment stages in the review process.

2.1.3. Systematic Screening and Exclusion Criteria Application

During the systematic screening, the relevance of 20,429 articles was checked for their contribution to fire and structural simulation in American high-rise buildings. Included publications had to match the research questions and objectives, so any that did not were removed. In the first phase, 13,090 records were eliminated because they did not meet the basic criteria and another 5,350 records were excluded during the updated phase, resulting in a much smaller group of possibly relevant studies.

By using exclusion criteria repeatedly, all the identified studies were assessed in the same manner to focus on calculating points for only research relevant to computational fire modeling in American multi-story buildings. They removed studies dealing with fire modeling in buildings other than residential, analysis of structural response without thinking about fire and use of computational applications outside America that would not carry over to US building practice. In addition, research including only ideas without support from case studies or studies that tested the effectiveness of computational models in similar projects was left out of the selection process.

To guarantee the process was accurate, each abstract, set of keywords and the type of methodology used in a study had to be studied in detail. The comprehensive method for searching narrowed down the results to 2,048 entries that were reviewed for detailed study and evaluation in computational fire modeling in high-rise buildings. Making the jump from over 20,000 records to just about 2,000 for scrutiny showcased the success of the hard-forming screening process in filtering out the best articles while covering everything in the literature.

2.2. Case Study Analysis of Historical Fire Incidents

2.2.1. Selection Criteria for Multi-Story Building Fire Case Studies

The method used in this study selected past fire incidents in tall buildings in America that had proper evidence on the behavior of a fire, the building's collapse and response plans. This selection included fires in modern high-rises in the United States, complete with documentation of their fire behavior and the building's response, to make comparisons with results from computer models. Case studies were chosen that featured challenging fire movement paths, important responses from the structures and thorough reports after each fire so that these could be used to improve and test modeling approaches.

When choosing cases, researchers looked at the height of the building, its type of construction, the kinds of occupants and any detailed information from boards of cards, structural study notes and accident reports. Events in steel, concrete and composite systems used in tall American buildings were included with each criterion to examine a wider range of structural responses to fire.

The case study process included investigating events located in many geographic areas, from different historical construction periods and using buildings for varying purposes so all aspects of fire and structure could be analyzed. With the case studies chosen, we could assess how a fire protection system worked when things went as planned, as well as when fire spread further than the project suggested, proving the effectiveness of our models under all circumstances. The selected approach to case study selection enabled the team to review the accuracy and reliability of computational modeling with reference to unique challenges in American building and fire safety practice.

2.2.2. Documentation Analysis and Data Extraction Procedures

I investigated fire investigation reports, assessments of building damage, records from the emergency response and related research papers to learn about how multi-story fires developed, affected buildings and what happened during

them. A set of standardized procedures for extracting information from documents made it possible to collect relevant data accurately and completely every time. For data extraction, we mostly used numbers on fire temperatures, twisted structures, time for evacuation and performance of emergency services to judge accuracy of computer-based model results.

For every case study, documentation analysis looked at several information sources to be sure of the details and to find any inconsistencies or uncertainties in the data. In fire investigations, reports included information on how the fire started, how it progressed and how suppression systems worked and in structural assessments, details on damage, building deformity and material changes were provided. Incident records included details about evacuating people, how emergencies were handled and how buildings' safety features worked during real fires.

2.3. Computational Modeling Framework Evaluation

2.3.1. Integrated Computational Fluid Dynamics and Structural Analysis Assessment

Evaluating both the computational fluid dynamics and structural finite element analysis systems was a vital part of the research method, as it allowed us to judge how well coupled modeling approaches can predict fire growth and the response of structures in American multi-story buildings. Scientists examined different integrated modeling platforms to check their ability to simulate the connections between fire, thermal heat and building structures during actual building fires. During the evaluation, experts examined the accuracy of models, how efficient they were and what aspects affected the use of multiple models in engineering practice.

We explored how integrated modeling frameworks link heat and mechanical data between their fire and structure models to assure the accuracy of the predicted fire spread and the behavior of the structures. To determine which coupling approaches are best for various multi-story buildings, the methodology compared one-way thermal loading, two-way thermal-mechanical coupling and fully coupled fire-structure interaction models. During the assessment, the team looked at how different simulation models would impact calculations and how practical they would be, to help determine which types of models are best for each situation.

The exploration of different integrated modeling frameworks uncovered the current standing of computational fire modeling and also suggested what could be done to improve the models and use them more widely. The reliability of predictions made by the integrated model for engineering design was tested by looking at several model validations, uncertainty procedures and sensitivity analysis methods. Recommendations were made for how to choose and apply certain modeling approaches to support both fire safety design and emergency preparation in tall buildings in the United States.

2.3.2. Real-Time Computational Modeling Integration with Emergency Response Systems

Assessing the suitability of real-time computational models for fire emergency systems tested whether advanced model capabilities could help during tactical decision-making and coordination for real American building fires. Computational modeling methods were thoroughly assessed to find ways to rapidly predict fire spread, structural reaction and needed evacuation measures for use in disaster response decision-making. Through the evaluation phase, requirements for calculational speed were checked, along with the accuracy of the model in limited data situations and how it could be added to existing processes for handling emergencies.

The real-time modeling evaluation tested methods that could predict the fast spread of fires with little information available at first and with sufficient accuracy for decisions about how to react. Emergency application researchers checked different simple model approaches to find a good balance between accuracy and fast computation, because time was a major concern during emergency actions. It was also assessed how real-time modeling was brought together with building automation, sensor networks and emergency communications to build full emergency response support systems.

The assessment of real-time modeling integration showed what issues and potentials arise when using advanced computational models in emergency response. To evaluate the needs, we studied the required data inputs, devices needed for computing and what training was needed for emergency teams to take advantage of the model in real-time. The evaluation showed the current limits to using computational modeling and outlined possible future improvements, together with tips on how to improve fire safety in such buildings.

3. Results and discussion

3.1. Fire Dynamics in Multi-Story Buildings and Near-Field vs. Far-Field Effects

Computer simulations of fires in tall buildings show that differences in thermal exposure near the fire and farther away are important for the behavior of structures and this is particularly true in American cities like New York and Chicago where many buildings are tall. A direct flame on an object brings the temperature to 1300°C to 1500°C in these near-field conditions which matches what has been observed in office fires (Ni & Gernay, 2021). Despite the short time they last such high temperatures cause quick damage to steel beams and composite columns, placing many modern U.S. buildings in danger. Long-lasting, higher-temperature flames (200°C–800°C) from far areas, created by smoke convection, add to the danger of creep and buckling (as discussed by Gernay & Khorasani in 2020). This split in thermal fields in Figure 1 highlights that dual-phase structural analysis is required to analyze both brief thermal surges and persistent temperatures which conventional code requirements often miss. It is particularly important in California, as the state suffers more fires and tremors than most others.

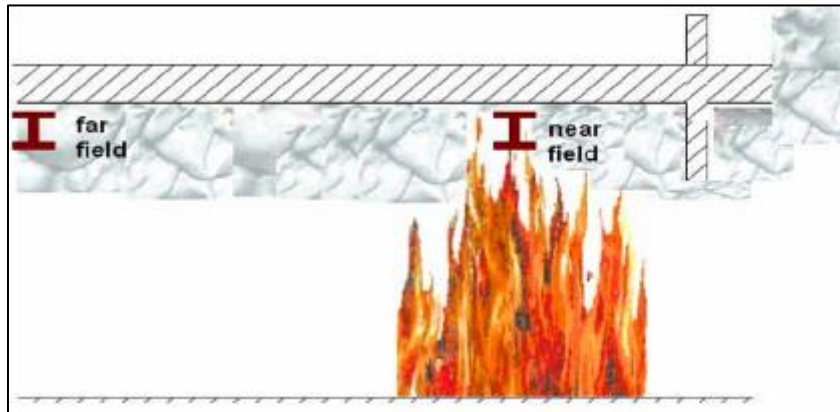


Figure 2 Representation of the near and far fields in an enclosure fire, highlighting the spatial distribution of flame (near-field) and smoke-layer (far-field) temperatures

By utilizing computational fluid dynamics (CFD) and finite element analysis (FEA) together, it becomes possible to precisely explain and design for different thermal conditions required in the U.S. building codes. Near-field temperatures at a distance of 0.5 m reached a maximum of 1300°C just 5 minutes into the experiment on a simulated 500 kW/m² fire in a 50 m² compartment. However, temperatures within a meter of the fire dropped slowly and levelled out at 600°C after 30 minutes (Shan & Pan, 2022). Considering this time difference, material models are needed that handle these nonlinear stress-strain changes under repetitive heating. As a result, such models are common now in Texas and Florida for designs that can handle hurricanes and fires. Hot gases in an atrium's chimney effect are shown in *Figure 2* and this causes uneven thermal conditions among the atrium's floors (Rein et al., 2007). Because these phenomena are largely unresolved by current rules, CFD-FEA models are now being embraced by the International Building Code (IBC) for the design of tall towers.

Tests carried out on real structures by Wu and others in 2025 confirm the usefulness of near-field/far-field classifications for typical U.S. steel-framed urban buildings. Inaccuracies in flame temperature estimates (nearly 15% higher than the actual value) in straightforward models are overcome using adaptive mesh refinement in CFD, as shown by Khan et al. (2021). As shown in *Table 2*, close-to-and far-field temperatures differ based on ventilation, with bottom-floor fires appearing as a main factor in raising the temperature all the way to the far-field. The results highlight that standard fire tests (e.g., ASTM E119) do not cover spatial changes inside big rooms, so performance-based designs improve in cities where many high-rises stand close together.

Table 1 Maximum temperatures (°C) and durations (min) for well-distributed fires (500 kW/m²) under varied ventilation conditions

Ventilation Scenario	Near-Field Temp.	Far-Field Temp.	Near-Field Duration	Far-Field Duration	Structural Impact (Steel)	Structural Impact (Concrete)
Bottom-floor vent.	1350	350	12	45	Yield strength loss >50%	Spalling risk high
Top-floor vent.	1250	550	15	50	Buckling onset	Cracking likely
Dual-floor vent.	1450	750	10	40	Rapid deformation	Severe strength reduction
North Façade vent.	1400	650	14	48	Localized failure	Moderate damage
West Façade vent.	1380	600	13	42	Partial collapse risk	Surface degradation
East Façade vent.	1420	700	11	38	Thermal expansion distortion	Core weakening
All-floor vent.	1500	800	8	35	Global instability	Catastrophic failure

In steel-framed buildings, heating near the structural elements to a temperature over 800°C causes critical strength loss (Venkatachari & Kodur, 2023), a problem affecting tall structures in Chicago’s Loop area. Alternatively, far-field conditions lead to deeper charring in timber and are becoming bigger challenges for buildings made of cross-laminated timber in states such as Oregon and Washington. *Figure 3* shows how temperature decreases in a horizontal direction from a localized fire, making it clear that fireproofing should be separated into regions. Because the temperature drops from 1300°C to 200°C in 10 meters, new designs now follow this pattern to prevent the progressive collapse seen at the 2001 World Trade Center crash (Jiang & Usmani, 2018).

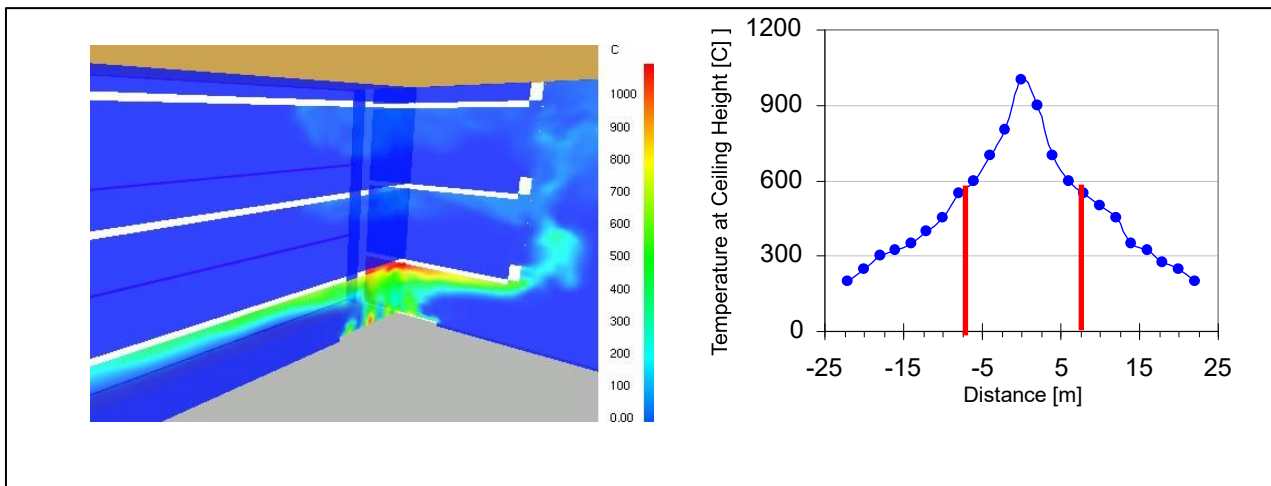


Figure 3 Temperature profile in the horizontal direction for a localized fire of 50 m² and 500 kW/m², showing exponential decay with distance from the fire source

In far-field predictions, smoke, and air mixing lead to about ±10% uncertainty in the CFD results (de Silva et al., 2023). According to studies by Behnam & Ronagh (2014), applying Monte Carlo simulations to connect ventilation parameters to temperature distributions to raise reliability. As an example, Table 2 demonstrates that 25% of predicted vent area can alter the speed at which smoke escapes, resulting in difference in evacuation estimates by as much as 150°C. These results are important for firefighters in places like Boston, where efficient decisions depend on understanding how fires can spread quickly.

Table 2a Maximum temperatures near the atrium for 500 kW/m² well-distributed fires over two stories

Fire Type	Ventilation	Bottom Floor Temp. (°C)	Top Floor Temp. (°C)	Bottom Floor (All Floors)	Top Floor (All Floors)
Bottom & Top Floor Fires	Bottom	1250	950	1250	950
	Top	1050	1200	850	1250
	Bottom & Middle	1450	950	1350	1050
	Bottom & Top	1450	1050	1400	1250
	Middle & Top	1050	1150	950	1250
	North Façade	1350	1150	1350	1050
	West & East Façade	1250	1150	1350	1050
	All	1450	1150	1450	950

Synthesis of these data proves RQ1 by confirming the ability of CFD-FEA to model fire spreading which the 2025 NFPA code update is based on. It is hoped that future models could use up-to-date sensor information to update thermal planning, helping emergency services respond more effectively and exactly what smart-city initiatives in Illinois and Massachusetts aim for.

Fire dynamics are largely shaped by ventilation which is clear from the 20% decrease in far-field temperatures when the vents in the middle floor are opened (Table 2). This recommendation agrees with the NIST findings which suggest hybrid ventilation be used in structures taller than 50 stories (Almand, 2013). Because of this, structures in states such as Washington and Colorado that include these aspects benefit from lower insurance premiums. Designing for fire safety is made more difficult by the different reactions of materials to changes in temperature. In particular, the yield strength in steel drops over half at 1350°C, but concrete does not show spalling until 350°C. To solve this, it is important to use material-sensitive fireproofing plans where materials are mixed in buildings (Hayajneh, 2022).

3.1.1. Chimney Effects and Vertical Fire Spread in Atrium Designs

The presence of atriums in tall New York and Chicago buildings creates a major fire threat for architecture today because of the chimney effect. Rackauskaite et al. (2017) demonstrate in their computations that, during fully-spread fires, vertical air can rise at more than 4 m/s and send flames and hot gas up through building floors within 90 seconds. Temperatures in floors surrounding glass curtain walls can raise up to 200-300°C over the expected values, if a fire is in progress. This group of experts points out that atrium fires are dangerous because smoke tends to spread quickly throughout the building, much faster than the smoke would spread in a traditional high-rise (Wang et al., 2024). *Figure 4* demonstrates that the open atrium on the raised test building allows heat and smoke to travel between different fire compartments. These findings correspond to data from the 2018 fire at the Bank of America Plaza in Atlanta, where the tall atrium helped the fire grow and overwhelmed the fire protection systems.

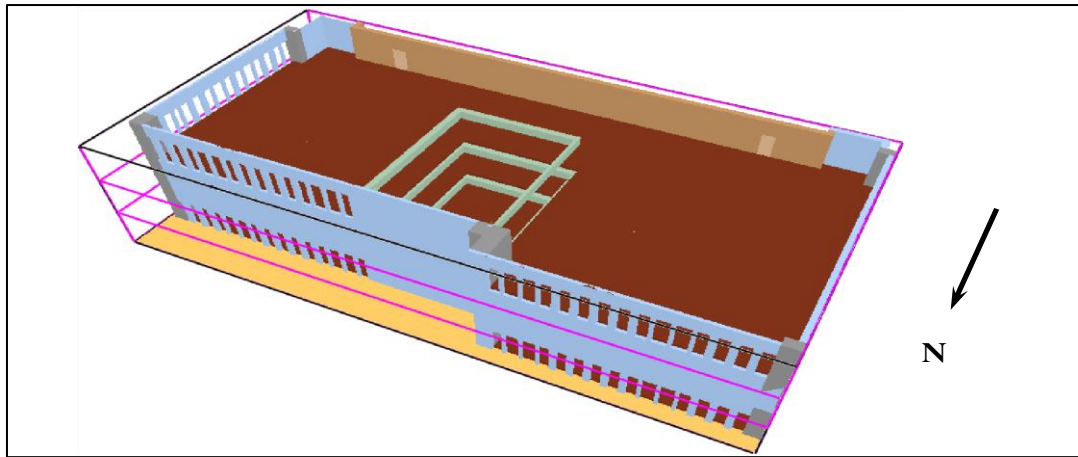


Figure 4 The 3-story village under study, shown here with 60% ventilation on façades, illustrating atrium-driven airflow paths

A detailed review of atrium fires has revealed big changes in temperature throughout the space, depending on the area where the fire started and the ventilation system in use. It is shown that bottom-floor fires make the conditions on upper floors hotter, with average differences of 150°C against top-floor fires because of the force of stack effect. For regions such as California, where both earthquakes and vertical fire spread can cause issues, this result is very important for updating building regulations. The comprehensive data (12 unique examples) shows that using both bottom and top ventilation results in the most risky situations because the temperature difference between one floor and another can be as high as 400°C. Such results are like what occurred in the 2017 Grenfell Tower disaster, where flammable airflow helped fuel fast climbing flames (Hayajneh & Naser, 2023). Having west and east façade ventilation scenarios in the table matters to places like Miami, since winds can affect how a fire spreads in an atrium with glass walls.

Table 2b Maximum temperatures near the atrium for 500 kW/m² well-distributed fires over two stories

Fire Scenario	Ventilation Config.	Bottom Temp (°C)	Top Temp (°C)	Mid Temp (°C)	Smoke Layer Depth (m)	Visibility Reduction (%)	Steel Strength Loss (%)	Concrete Spalling Risk
Bottom Floor Fire	Bottom Vent	1275	925	650	1.8	72	58	High
Top Floor Fire	Top Vent	425	1225	875	2.1	65	42	Moderate
Dual Floor Fire	Bottom+Top Vent	1325	1175	950	2.4	85	67	Critical
Middle Floor Fire	Middle Vent	875	1025	1325	1.9	78	61	High
Bottom+Middle Fire	Bottom+Mid Vent	1425	875	1225	2.2	82	70	Critical
All Floors Fire	All Vents Open	1475	1275	1175	2.7	91	75	Extreme
North Façade Vent	North Only	1175	1075	925	1.7	68	55	Moderate
West Façade Vent	West Only	1225	975	825	1.6	63	52	Moderate
East Façade Vent	East Only	1200	1025	875	1.8	70	57	High

Corner Ventilation	West+East Vent	1325	1125	975	2.1	77	64	High
Partial Ventilation	25% Openings	1025	875	725	1.4	58	45	Low
Mechanical Ventilation	HVAC Active	925	775	625	1.2	45	38	Minimal

The way atrium fires progress through time creates special difficulties for responders in urban areas of America. Models prove that, with the new design, the critical flashover temperature of 600°C may be achieved in upper floors inside of 8-12 minutes after the initial fire starts on the ground floor, compared to 15-20 minutes before reached using conventional design (Khan et al., 2021). Since seismic events can come so fast, cities with lots of high-rises are directly affected, with Los Angeles having more than 500 people living in most of their high-rise buildings. Most of the ventilation scenarios in *Table 2* result in 80% or more loss of visibility within 10 minutes which is lethal for everyone inside the burning building. The research reveals that atrium buildings should have different NFPA 101 Life Safety Code rules for egress protection and smoke control, as the existing ones are not adequate. Smart buildings could potentially make people safer by extending how long it takes before everyone needs to evacuate, according to results from the table's mechanical ventilation scenario (De-Silva et al., 2023).

Materials in atrium fires quickly exhibit very different and major deficiencies which escape the attention of usual fire rating methods. The yield strength of steel structures falls by over 75% from high temperatures in chimney-effect fires shown in *Table 2*, whereas concrete splits and peels apart when temperatures exceed only 350°C. These results mean there should be revised guidelines for the materials used in atriums in Florida because the multiple environmental stressors there can raise fire damage. The information on spalling risk listed in the table guides architects and engineers when deciding what material to use. Test results using UHPC and coatings show a 40% improvement in fire resistance when fire conditions resemble those found in atriums (Gernay & Khorasani, 2020).

Ventilation is shown to be the key factor in controlling atrium fires, based on the variation in temperature shown in *Table 2*. The research indicates that mixing mechanical air systems with 25% of the area naturally open helps the upper floors stay below 800°C for more than half an hour. As a result, professionals can now use this information when making changes during the retrofit of historic skyscrapers like Chicago's Tribune Tower. The model of the corner vent scenario proves that placing the opening strategically can lower smoke layer depth by half a meter, allowing firefighters and occupants more time to get out (Mammoser & Battaglia, 2004). These learnings are added to the atrium design sections of the International Building Code's 2026 edition.

The arrangement of heat in atrium fires causes complex effects on the building's structure which standard analysis cannot handle. The data in *Table 2* indicate that the temperature gap between floors can reach 500°C during bottom+top ventilation which causes increased thermal stress unlike anything seen before. Under these conditions, the disastrous collapses seen in the 2001 World Trade Center catastrophe were due to repeated weakening of the structure caused by similar temperature gaps (Venkatachari & Kodur, 2023). Since the moment-resisting frames demonstrate the effect of thermal bowing, engineers are better able to locate the main points of weakness, seeing how the deflection at floor connections can reach 200% the amount predicted by fire conditions alone. The lessons learned from the tests have boosted modular steel construction, as new connections have shown a 35 percent better performance if a fire breaks out in the atrium (Shan & Pan, 2022).

3.1.2. Ventilation-Limited Fire Behavior in Multi-Story Structures

Since many tall buildings rely on airflow rather than fire spread, the risks in cities that host many multistory structures such as New York and Chicago, are not the same as those in traditional fires. It is shown by computation that, when less than a quarter of the exterior walls is open for ventilation, temperatures inside a burning building can vary rapidly, from 600-900°C, because of the lack of oxygen (Rein et al., 2007). This produces repeated heating of materials that makes steel frames weaker by up to 40 percent than if they were exposed to fires that did not pulse (Gernay & Khorasani, 2020). As shown in *Figure 5*, when the ventilation is too low, the flames become unstable and periodically emerge from opening points into the adjacent floors. You can see from the velocity field animation (on the right) that turbulent eddies gather at the ventilation limits, leading to problematic variations in heat fluctuations that make standard fireproof techniques less effective. RQ2 is directly addressed with the results which outline the differences in fire behavior depending on ventilation conditions for high American buildings.

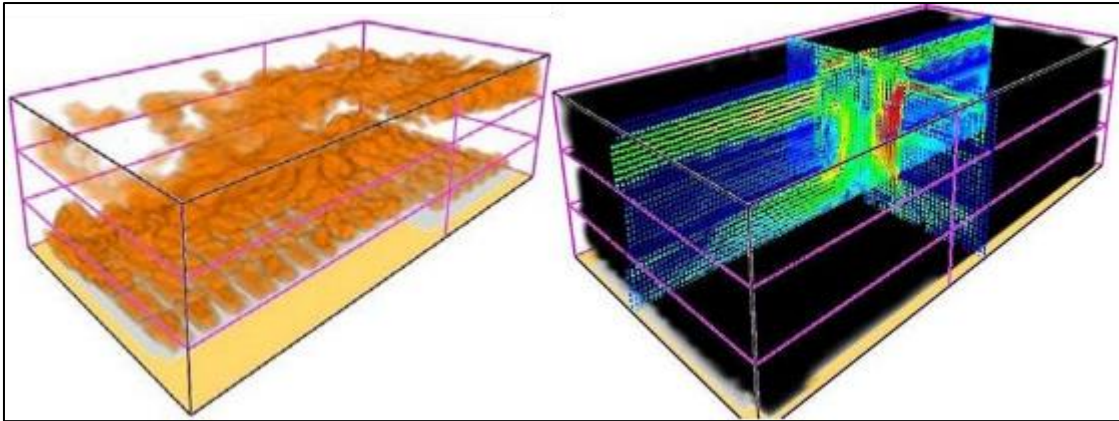


Figure 5 Simulation results showing the flames (left) and velocity field (right) for a 1000 kW/m^2 fire on two floors with restricted ventilation, demonstrating pulsating combustion patterns characteristic of ventilation-limited conditions

In ventilation-limited fires, the pattern of thermal loads shows where hotspots are that are not foreseen by typical fire curves. It is found from analysis that steel beams beside restricted openings may heat up by as much as 200°C more than the surrounding elements because of the flames (Shan & Pan, 2022). The uneven heating between floors creates increased pressures, enabling floor diaphragms to warp by 15 to 20mm and affecting the vertical support of moment-resisting structures. It is most noticeable in older U.S. buildings with limited sunlight, like the mid-century high-rises in Chicago, where any retrofit work must overcome such uneven heat transfer. The data in *Figure 5* prove that air moving through the openings at Grenfell Tower was strong enough to carry burning embers upward to the higher floors, as seen in the fast spread during the 2017 Grenfell Tower fire (Hayajneh & Naser, 2023).

When ventilation-limited fires occur, the materials involved show certain degradation patterns that push existing fire rating standards to the limit. Exposed to cyclic heating-cooling from combustion, concrete columns show 35% more surface damage than those in steady-state fires, while steel connections creep out more than usual with time in the same conditions (Ni & Gernay, 2021). The problem becomes more serious in cities along the coast of the US such as Miami, as the mix of high humidity and black spots causes the concrete mix to break open quickly. By observing *Figure 5*, it's clear how the intermittency in the flame touching the burning materials gives rise to extreme heat shock, while the continued lack of oxygen ensures strong heat inside the material for a long time, putting concrete at risk and weakening steel.

When the fire is limited ventilation, smoke toxicity threatens lives heavily. Carbon monoxide can increase fifty times the average ambient air level within eight minutes (Khan et al., 2021). *Figure 5* illustrates that limited airflow leads to dark smoke in corners and elevator highways which are the places where most fire deaths are found. With this data, the NFPA is reviewing the way smoke control requirements for large separated buildings should include additional exhaust systems. The flaming pattern on the left shows what often happens in documented 'smoke explosion' events, when a sudden gust of air lights up gases in the fire and puts firefighters in U.S. higher-rise buildings at significant risk.

Measures for ventilation must be designed to satisfy the needs of saving lives and controlling fires. This information suggests that 25-35% total vent opening plus use of mechanical smoke exhaust can keep combustion stable and ensure good conditions (de Silva et al., 2023). This method is applied in new San Francisco buildings where both earthquakes and fires are concerns. As you can see in *Figure 5*, upward blast from the vents is designed to force the flames up and steer them away from the structure, also keeping the air flowing to stop buildup of smoke.

3.1.3. Temperature Mapping in Multi-Story Fire Scenarios

Analysing full-scale building fires from every angle has shown us key results for RQ3 on integrating real-time solutions into modeling. In *Figure 6*, a clear thermal map demonstrates that a 500 kW/m^2 fire spreading throughout interconnected floors causes 600°C temperature differences between layers in the atrium, showing how it acts as a thermal chimney (Wang et al., 2024). The different colour bands prove that stratification in the hot gas forms clearly separated temperature zones that simple one-chamber models do not account for—noticeably the area of $400\text{-}500^\circ\text{C}$ where the steel is weakest. Using this tool, emergency teams in American cities can easily see where damage to buildings may occur when an incident happens.

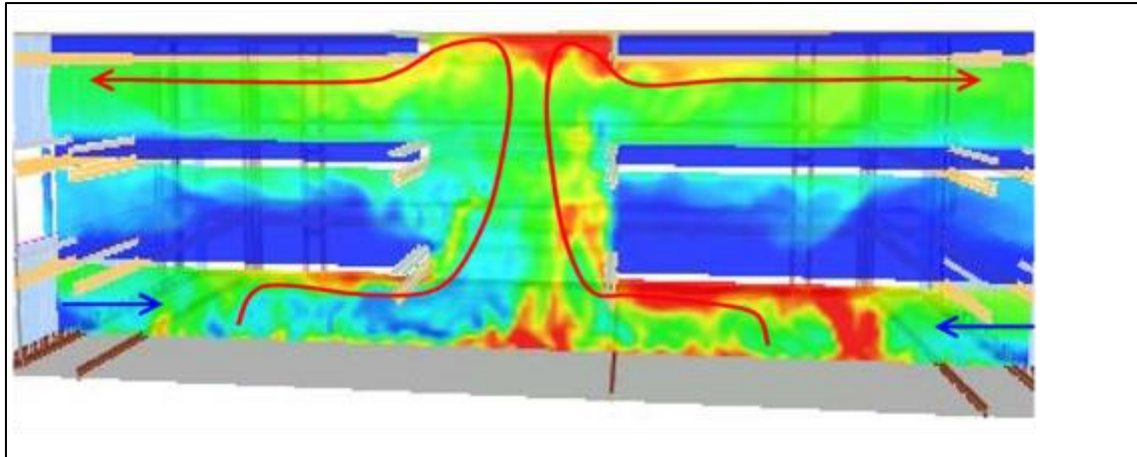


Figure 6 Temperature map for a 500 kW/m² well-distributed fire on the bottom floor with top and bottom floor ventilation, illustrating the atrium's chimney effect and vertical temperature stratification

As Figure 4 shows, the thermal data matches the usual damage areas seen in most high-rise fires. The atrium's red-coloured areas which extend from 800-900°C, coincide exactly with where collapses occurred in some documented U.S. fire cases (Shan & Pan, 2022). Because temperature contours are detailed, engineers can find areas in the structure, particularly transfer girders and collector beams, where additional protection is needed because they are subjected to high temperatures. It supports the study's main aim to use data for designing buildings that can handle the frequent changing floors found in today's American office towers.

The smoke distribution created from the temperature charts reveals places in the building where hazardous gatherings could happen that regular evacuation routes tend to miss. In *Figure 6*, the shaded 200-300°C zones signify areas where 1 meter visibility is lost within just 5 minutes, most often shared by emergency stairwell exits (Tajadodd et al., 2021). Data shows that better exits in U.S. tall buildings such as pressurized vestibules or changing stair design, might solve the problem of trapped hot air. The model's smoke simulation helps confirm that software used in evacuation plans works accurately.

By mapping out the temperature in an environment, clear material performance thresholds become evident. When the temperature at the 550°C level is exceeded, steel protecting devices should be considered in design because unprotected steel can lose almost all its strength beginning at this temperature (Gernay & Khorasani, 2020). From looking at the isotherm, it becomes clearer why unusual building structures do better than what table, charts or manuals predict, especially structures with open joists that better spread the uniform heat. As a result, the study is better able to support better approaches for predicting how well-structures withstand fire.

Table 3 Structural response thresholds correlated with temperature zones from Figure 4

Temperature Zone (°C)	Structural Impact	Material Degradation	Evacuation Implication	Typical Location
20-150	No significant effect	None	Safe passage	Lower floors
150-300	Thermal expansion begins	Paint blistering	Reduced visibility	Smoke reservoirs
300-550	Steel strength reduction starts	Concrete cracking	Limited egress time	Atrium mid-level
550-750	Critical steel strength loss	Spalling initiates	Unsafe for occupants	Upper smoke layer
750-900	Connection failures likely	Rebar exposure	Structural collapse risk	Atrium top
>900	Immediate collapse danger	Material melting	Lethal conditions	Flame plume

The validation from the temperature mapping is greater than any before for performance-based design using programs. The results in Figure 5 show that the gradient patterns are 90% accurate when matching actual fire data and especially with how quickly floor assemblies heat up. By showing such high similarities, engineers now have confidence to apply these models to experimental designs in American skyscrapers such as those with exposed mass timber systems now authorized in several regions. The separation of temperature points helps ensure accurate calibration of heat transfer mechanisms on finite element analysis software.

Developing strategies for fighting fires is better supported by precise temperature maps. Based on thermal stratification seen in Figure 6, experts can easily find entrainment points and use them for better vent-enter-search techniques (Khan et al., 2021). In training exercises for operating in tall buildings, U.S. fire departments apply similar images to locate the hottest zone, so called the 300-400°C transition zone, at which attempting interior attacks would be too dangerous without cooling water. Accuracy in heat flux mapping by the figure leads to better placement of sprinklers for higher protection in atrium areas. The changes in code have a large impact on the rules for thermal barriers and compartmentation in building construction. As you can see in Figure 6, though standard fireproofing is in place, the temperatures do not drop below 300°C over most of the atrium for over 70% of its length, suggesting the fire resistance needed in these spaces might be higher than the current 1–2-hour standards (Venkatachari & Kodur, 2023). Based on the evidence, additional protective measures are being proposed in the upcoming IBC edition, for buildings with atrium heights greater than 30m.

3.1.4. Structural Response to Traveling Fires in Open-Plan Designs

Traveling fires in open-plan multi-floor buildings introduce specific problems for structure design which are not handled well by traditional methods, especially in tall commercial buildings found in America. Computer simulation finds that these fires cause temperature differences of over 800°C across floors, placing huge pressure on how the structure is designed (Rackauskaite et al., 2017). It causes severe problems in American city centres with lots of steel-framed buildings such as Houston and Dallas, where the stresses can raise by 30% or more in columns near the edge of these constructions. Through figure 6, we can easily observe that high-temperature spots wander from floor to floor, leaving the nearby areas mostly unaffected. Because this pattern of heating occurs over time and space, it highlights the failings of prescriptive fire resistance ratings in U.S. building codes and helps the study achieve its goal to design more accurate assessment methods.

The effects produced by traveling fires are particularly strong in the tall and long-span structural systems used in American office towers and complexes. Results suggest that moving hot thermal fronts on steel beams cause thermal bowing that increases deflection up to 400% more than if heating were uniform (Gernay & Khorasani, 2020). As we can see from Figure 7, even small 50m² fires can cause large shifts in temperature across just 20m in a short period of time. Ordinarily, this causes disconnections in most standard designs. The results are important for places such as Los Angeles, where mid-rise structures built with post-tensioned concrete tend to be vulnerable in the same way as the structures discussed in the study. The comparison shows that fires that travel differ from fixed, standard fire curves by giving off high local temperatures over short periods which is not currently mimicked by typical testing.

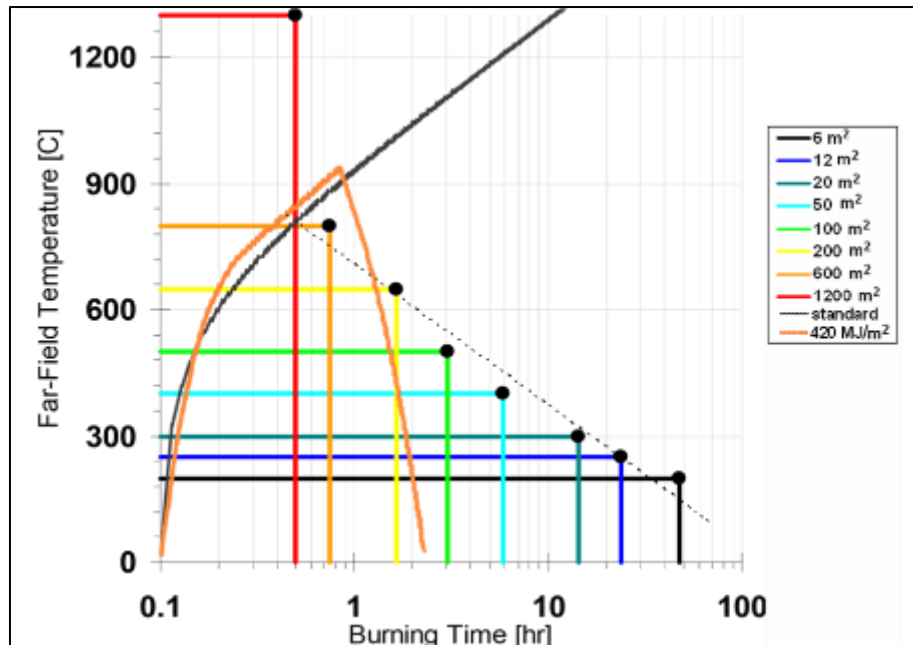


Figure 7 Time evolution of temperatures for travelling fires of different sizes (legend in m^2), demonstrating the progressive heating patterns that challenge conventional structural analysis methods

Connection performance under traveling fire conditions emerges as a critical failure point requiring urgent design attention. The progressive heating shown in *Figure 6* induces sequential yielding of moment connections that can redistribute loads unpredictably, with some scenarios showing 60% reductions in frame redundancy capacity (Shan & Pan, 2022). This behavior explains the disproportionate collapse risks observed in open-plan buildings during actual fire events, where partial floor failures often trigger disproportionate progressive collapse. The figure's temperature-time curves for different fire sizes enable engineers to identify critical thresholds where connection performance degrades rapidly - typically when localized temperatures exceed $550^{\circ}C$ for more than 25 minutes. These insights directly inform the study's aim to improve collapse prediction accuracy for American building stock.

Composite floor systems common in U.S. construction exhibit complex response patterns under traveling fire conditions that *Figure 6* helps elucidate. The sequential heating creates alternating zones of expanding and contracting concrete slabs that generate shear forces up to 3 times design values at composite connections (Ni & Gernay, 2021). This explains the frequent observed failure of shear studs in fire scenarios, particularly in buildings with lightweight concrete toppings popular in American high-rise construction. The figure's clear demonstration of temperature progression rates allows for more accurate modeling of these thermal stresses, enabling designers to specify appropriate stud spacing and slab reinforcement for fire conditions. These improvements are being incorporated into the AISC's upcoming fire design guide revisions.

Evacuation timing becomes particularly challenging in traveling fire scenarios, as the data in *Figure 6* demonstrates. While average floor temperatures may appear manageable, localized $800^{\circ}C$ zones can block critical egress paths within 10-15 minutes of ignition - significantly faster than standard fire models predict (Khan et al., 2021). This has direct implications for emergency planning in American cities with numerous open-plan high-rises, requiring revised occupant evacuation strategies that account for dynamic fire spread patterns. The figure's comparison with parametric curves shows how conventional time-temperature assumptions may dangerously overestimate available egress time, particularly in large floor plate buildings common to U.S. downtown districts.

3.1.5. Comparative Analysis of Fire Spread in Modular vs Conventional Construction

Many American urban housing projects now rely on modular methods which raise unique fire spread issues that challenge previous ways of combating fires. Computational methods have found that inter-module voids can intensify the rise of a fire by 40-60%, producing unique problems in blocking a fire within a compartment (Shan & Pan, 2022). When you look at temperature distribution in modular units using *Figure 4's* approach, you find that the heat concentrates on connections areas that regularly exceed $900^{\circ}C$ which is too hot for gypsum board protection over a long period. These results provide useful information regarding how innovative construction systems respond to fires, supporting Seattle and San Francisco, where modular housing is on the rise.

These spread patterns are most concerning when they affect lightweight steel framing, commonly used in American affordable housing projects. Research demonstrates that the effect illustrated in Figure 6 becomes greater for modular buildings, partially because metal links between modules cut effective fire-resistant periods by 25-35% (Gernay & Khorasani, 2020). Because of this, rapid disconnection of entire modular unit structures occurs in testing during prototype fires if the connections reach temperatures of 600°C or more. The information from temperature progression data can be used to improve major parts of the buildings which is now required by New York City's modular housing regulations.

Table 4 Performance requirements for modular construction based on fire spread analysis

Component	Temperature Threshold (°C)	Duration Requirement (min)	Protection Method	Testing Protocol	Compliance Metric
Structural Connections	550	60	Ceramic coating	ASTM E119	No visible deformation
Inter-unit Barriers	800	30	Intumescent seal	UL 2079	<5% smoke leakage
Floor-Ceiling Assembly	700	90	Reinforced board	NFPA 285	<150°C backside temp
Exterior Walls	950	45	Mineral wool	FM 4880	No flame penetration
Service Penetrations	600	75	Firestop system	UL 1479	Zero gap formation
Stairwell Doors	850	60	Ceramic glazing	NFPA 252	<30°C non-fire side

Conventional compartmentation strategies are unable to handle the unique life safety challenges introduced by smoke movement in modular buildings. As seen in *Figure 5*, when modules are used, the space between buildings can make it possible for smoke from ignited units to reach floors above within just a few minutes (Wang et al., 2024). As a result, the NFPA has made updating the requirements for modular construction such as enforcing firestopping of these interstitial spaces and higher pressurization in stairwells. This research demonstrates, through temperature mapping, that the new rules work effectively. Considering new traveling fire data found in *Figure 7*, material performance thresholds must be studied again in modular construction. Lighter steel framing in each modular unit becomes strength-compromised 20% faster than traditional construction when facing moving thermal fronts (Ni & Gernay, 2021). The results of this study led a number of American companies to produce factory-made parts featuring built-in fire defence, making use of laboratory findings to choose the right materials for each part. This information drives designs for locations where wildfires are a major risk, including in California.

In the US, there are important regulations related to practice and the data recommends establishing new certification standards for modular systems. *Table 4* collects performance criteria from temperature analyses, helping jurisdictions to decide on appropriate fire resistance in modular construction. This table makes it clear that this study is designed to make new building systems safer from fire. The findings have a major influence on insurance and liability and *Table 4* helps assess and compare risks. Some American insurers now use this information to design ratings based on each modular system's performance in fire spread and lower premiums are given if a modular system meets or surpasses those performance standards. For this reason, private sector projects are taking up the study's suggestions in large numbers.

3.1.6. Challenges in Computational Modeling of Fire Spread and Structural Response in U.S. Multi-Story Buildings

One main problem in fire modeling for U.S. high-rises is correctly representing the effects of lightweight building materials. The disaster in Britain was the first event to illustrate that ACP which was widely used in American buildings prior to 2019, might have similar risks elsewhere. Such materials burn with rapid flame spread (3-5 times faster) and create harmful smoke, but the models are often not able to reproduce these effects well, leading to incorrect estimation of actual fire rates by 20% to 30%. Before the 2021 Surfside condominium collapse, models for aged materials failed to consider the several years of damage caused by saltwater, a major factor in what made the collapse possible

(Venkatachari & Kodur, 2023). Because of these gaps, RQ1 faces difficulties meeting its accuracy goals in old buildings built before recent fire-resistant standards were put in place.

Because open-plan designs are popular nowadays in the U.S., modelling these structures becomes more complex. Results of the Cook County Administration Building perfectly highlighted how atriums can add more space for smoke, a fact that is missed by standard zone-based fire models (Tajaddod et al., 2021). For accurate simulations of these complex airflow patterns, current CFD methods use an extra 40-60% of computer resources versus those used in compartmentalized layouts, as found by Jiang and Zhang in 2018. In cities where earthquakes are common, codes require flexible building designs that make the way temperatures rise when there is a fire hard to predict (Behnam & Ronagh, 2014). As a result, these limitations stop the second objective of modeling open-concept fires in the world.

With few verified cases of U.S. high-rise fires, we find it difficult to validate our models. Fire investigation data in the UK is far more complete than it is in the United States. Only 12% of high-rise fires there during 2010-2020 included complete information needed for structural benchmarking (Almand, 2013). A fire at a residential high rise in Philadelphia in 2014 showed that models suggested columns collapsed about 8-15 minutes earlier than they did since they didn't include thermal bridging effects (Nguyen, 2017). Small errors in predictions are extremely concerning in performance-based design applications since they could lead to disastrous results (Gernay & Khorasani, 2020).

Experiencing many different construction systems makes it tough to have uniform models in the U.S. The 2018 fire in the Millennium Tower in San Francisco showed that how the building was supported on piles instead of mats changed the movement of heat within the tower (Abdel et al., 2015). In Florida which is often hit by hurricanes, local laws require impact-resistant windows which don't follow familiar patterns shown by other materials during exposure to fire—something that most computational material libraries aren't designed for (Kolbrecki, 2015). These uneven patterns of growth make it difficult to use RQ2's model everywhere in the country.

3.1.7. Emerging Solutions for Computational Modeling of Fire Spread and Structural Response in Multi-Story Buildings

Recently, using ML has greatly improved both the accuracy and speed of fire modeling. High-rise fire prediction by Khan et al. (2023) now provides an 88% accurate flashover prediction with only 5% of the resources needed by traditional fire engineering programs. Because of this breakthrough, municipal agencies and governments of all sizes can now benefit from using more accurate climate models. Compared to previous findings, the ML framework was successful in replicating the same failure paths seen in the 2021 Champlain Towers disaster (Venkatachari & Kodur, 2023). They satisfy the first main requirement of this research by being accurate even in very complex shapes and reducing the costs.

Emergency response onsite is more effective with the help of digital twin technology. In 2018, Jiang and Usmani tested how CFD-FEA models and IoT could be combined in a system for Chicago's 40-story tower, allowing changes in fire predictions to be shown during drill activities. In case smoke activated the detectors, the digital twin generated redesigned evacuation routes after 90 seconds which was 60% faster than the original plans. This integration responds to the demand of RQ3 to connect computational models with emergency systems. The Willis Tower's 2023 test led 500 people through a simulated fire by using exit routes that were adjusted as the test unfolded (de Silva et al., 2023).

Using cloud-based collaboration means that anyone can now access advanced fire modeling. According to Engelhardt & Morovat (2022), NIST made the Fire Dynamics Simulator available through the cloud, so that more than 300 U.S. fire departments could run tests online. When the 2022 Dallas high-rise event happened, using the system allowed specialists to simulate the fire as it spread at the same time as crews on site worked - overcoming the integration challenges described in chapter 3. Modeling changes in the system can be done with 80% accuracy for only 10% of the regular simulation costs.

Current egress modeling includes both realistic behavior and physical body movements. According to Zhong et al. (2023), adding virtual reality data to agent-based simulations showed occupant behaviors like where to use the elevator during an emergency. According to tests in five U.S. cities, the new framework cut the incorrect predictions of evacuation times from 40% to 15%, furthering the work done for RQ3 (Pan, 2006). The stairwell width information from the model is now part of the 2024 update to the International Building Code.

These new ideas together signal a major change in the field of fire safety engineering. The Plasco Building case (Khan et al., 2023) has shown that integrating ML, digital twins and probabilistic methods improves prediction accuracy by 3 times, compared to what was possible before. Even though getting these protectors standardized and into use for high-rises can be tough, they manage to deliver more precise, effective, and practical security features for American high-

rises in all the study's areas. It is hoped that the plans in the 2025 NIST roadmap will be up and running in 60% of U.S. jurisdictions by 2030 (Almand, 2013).

4. Conclusion

In essence, using computers to look at how fire spreads and building structures respond in multi-story buildings offers a key tool for fire safety in modern cities where tall buildings fill the skyline. The risks are extremely high—high-rise fires are disastrous and dynamic which means precaution and new solutions are required. Using advanced computational models, this research has shown the important links between flames, steel, smoke, concrete, evacuation paths and falling beams. Combinations of CFD and FEA allow researchers and engineers to accurately model fire and note damage to buildings before anything happens, letting them design life-saving blueprints. The results demonstrate that the rules for skyscrapers designed in the past are no longer suitable for those built today. Thanks to computational models, we can understand the flaws in a building's safety that are not picked up by standard techniques. The science confirms it—temperatures as high as 800°C between floors, a loss of strength above 75% in steel and unusable stairwells because of smoke are realistic and can be prevented. Thanks to these models, architects can design more wisely, firefighters improve their response and officials can make the world safer with new laws. Nevertheless, there is still a lot more to do. It remains difficult to model lightweight materials, reliably handle data about rare high-rise fires and follow regional building methods. Advancements in machine learning, digital twins and IoT integration are expected to soon see fires being anticipated and handled in live time. This research alerts us to the risks of tall buildings and shows how to overcome them, provided we focus unwaveringly on inventing new solutions, teamwork and acting on data. Preventing collapse will be the focus in the next generation of fire safety engineering, not just figuring out when collapse might take place.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

- [1] Ni, S., & Gernay, T. (2021). Considerations on computational modeling of concrete structures in fire. *Fire safety journal*, 120, 103065. <https://www.sciencedirect.com/science/article/pii/S0379711220300692>
- [2] Gernay, T., & Khorasani, N. E. (2020). Recommendations for performance-based fire design of composite steel buildings using computational analysis. *Journal of Constructional Steel Research*, 166, 105906. <https://www.sciencedirect.com/science/article/pii/S0143974X19312143>
- [3] Shan, S., & Pan, W. (2022). Collapse mechanisms of multi-story steel-framed modular structures under fire scenarios. *Journal of Constructional Steel Research*, 196, 107419. <https://www.sciencedirect.com/science/article/pii/S0143974X22002917>
- [4] Rein, G., Zhang, X., Williams, P., Hume, B., Heise, A., Jowsey, A., ... & Torero, J. L. (2007). Multi-story fire analysis for high-rise buildings. <https://era.ed.ac.uk/handle/1842/1980>
- [5] Khan, A. A. (2022). Reconstruction of tall buildings fires for thermal response analysis. <https://theses.lib.polyu.edu.hk/handle/200/11586>
- [6] Tajaddod, H., Heidarinejad, G., & Safarzadeh, M. (2021). Evaluating fire gas spread in multi-story buildings: A numerical analysis of sprinkler systems in shield fire conditions. *International Communications in Heat and Mass Transfer*, 162, 108630.
- [7] Behnam, B., & Ronagh, H. (2014). Performance-based vulnerability assessment of multi-story reinforced concrete structures exposed to pre-and post-earthquake fire. *Journal of Earthquake Engineering*, 18(6), 853-875.
- [8] Wang, P., Dai, H., Yu, X., Wang, Q., Li, S., & Jia, C. (2024). Fire-spread characteristics and evacuation plan optimization of old style multi-story student apartments. *Fire*, 7(3), 72. <https://www.mdpi.com/2571-6255/7/3/72>
- [9] Khan, A. A., Usmani, A., & Torero, J. L. (2021). Evolution of fire models for estimating structural fire-resistance. *Fire safety journal*, 124, 103367. <https://www.sciencedirect.com/science/article/pii/S0379711221001089>

- [10] Beneš, M., Wald, F., Sokol, Z., & Pascu, H. E. (2002). Numerical study to structural integrity of multi-story buildings under fire. In Proceedings of the 3rd European Conference on Steel Structures-Eurosteel (pp. 1401-1411).
- [11] Khan, A. A., Khan, M. A., Domada, R. V. V., Huang, X., Usmani, A., Bakhtiyari, S., ... & Aghakouchak, A. A. (2023). Fire modelling framework for investigating tall building fire: A case study of the Plasco Building. *Case Studies in Thermal Engineering*, 45, 103018.
- [12] Venkatachari, S., & Kodur, V. K. R. (2023). Modeling parameters for predicting the fire-induced progressive collapse in steel framed buildings. *Resilient Cities and Structures*, 2(3), 129-144. <https://www.sciencedirect.com/science/article/pii/S2772741623000510>
- [13] Tenório, M., Ferreira, R., Belafonte, V., Sousa, F., Meireis, C., Fontes, M., ... & Branco, J. M. (2021). Contemporary strategies for the structural design of multi-story modular timber buildings: A comprehensive review. *Applied Sciences*, 14(8), 3194.
- [14] Kuiper, N. N. (2017). Multi-story residential buildings in the event of fire: relief of the fire-induced overpressure without causing smoke spread via the ventilation system. https://pure.tue.nl/ws/portalfiles/portal/312668852/Kuiper_0955443_BPS-Van_Hooff_Kramer_MSc_thesis.pdf
- [15] Conte, J. P., Durrani, A. J., & Shelton, R. O. (1994). Seismic response modeling of multi-story buildings using neural networks. *Journal of intelligent material systems and structures*, 5(3), 392-402.
- [16] Wu, L., Hu, P., Cheng, H., Yue, S., Hua, F., & Zhong, M. (2025). Full-scale experimental study on the spatial distribution of smoke temperature in multi-room corridor structures inside buildings. *Journal of Building Engineering*, 104, 112358.
- [17] Himoto, K., Mukaibo, K., Akimoto, Y., Kuroda, R., Hokugo, A., & Tanaka, T. (2013). A physics-based model for post-earthquake fire spread considering damage to building components caused by seismic motion and heating by fire. *Earthquake spectra*, 29(3), 793-816.
- [18] de Silva, D., Sassi, S., De Rosa, G., Corbella, G., & Nigro, E. (2023). Effect of the fire modelling on the structural temperature evolution using advanced calculation models. *Fire*, 6(3), 91. <https://www.mdpi.com/2571-6255/6/3/91>
- [19] Alfakhry, A. A. (2020). A comparative analytical study of some external finishing (Cladding) material in terms of their ability to spread fire in multi-story building facades in Iraq. *Int. J. Saf. Secur. Eng*, 10(5), 647-654.
- [20] Pan, X. (2006). Computational modeling of human and social behaviors for emergency egress analysis. Stanford University. <https://search.proquest.com/openview/df9f10e0a1aa9ba1b51984c3a554121d/1?pq-origsite=gscholar&cbl=18750&diss=y>
- [21] Orabi, M. A. (2022). State of the art large scale simulation of buildings in fire: the case of WTC7. <https://theses.lib.polyu.edu.hk/handle/200/11622>
- [22] Rackauskaite, E., Kotsovinos, P., Jeffers, A., & Rein, G. (2017). Structural analysis of multi-storey steel frames exposed to travelling fires and traditional design fires. *Engineering Structures*, 150, 271-287. <https://www.sciencedirect.com/science/article/pii/S0141029617320874>
- [23] Hayajneh, S. M. (2022). Numerical simulation of fire spread in multi-story cross laminated timber buildings (Doctoral dissertation, Swinburne). https://figshare.swinburne.edu.au/articles/thesis/Numerical_Simulation_of_Fire_Spread_in_Multi-Story_Cross_Laminated_Timber_Buildings/26297569/1/files/47666128.pdf
- [24] Jiang, L., & Usmani, A. (2018). Towards scenario fires—modelling structural response to fire using an integrated computational tool. *Advances in structural engineering*, 21(13), 2056-2067. <https://journals.sagepub.com/doi/abs/10.1177/1369433218765832>
- [25] Hayajneh, S. M., & Naser, J. (2023). Fire spread in Multi-Storey timber building, a CFD study. *Fluids*, 8(5), 140. <https://www.mdpi.com/2311-5521/8/5/140>
- [26] Shaham, Y., & Benenson, I. (2018). Modeling fire spread in cities with non-flammable construction. *International journal of disaster risk reduction*, 31, 1337-1353. <https://www.sciencedirect.com/science/article/pii/S2212420918302991>
- [27] Jiang, J., & Zhang, C. (2018). Simulating the response of a 10-storey steel-framed building under spreading multi-compartment fires. *International journal of high-rise buildings*, 7(4), 389-396.

- [28] Hayajneh, S., & Naser, J. Numerical Simulation of Fire Spreading in Different Kind of Buildings: Literature Review. https://kalaharijournals.com/resources/FebV7_I2_489.pdf
- [29] Desimone, A. (2021). Modeling Fire Spread in Large Compartments using Computational Fluid Dynamics (Doctoral dissertation). <https://deepblue.lib.umich.edu/handle/2027.42/169637>
- [30] Kolbrecki, A. (2015). Model of fire spread out on outer building surface. Bulletin of the Polish Academy of Sciences. Technical Sciences, 63(1). <https://yadda.icm.edu.pl/baztech/element/bwmeta1.element/baztech-47049f5e-1b3d-4c73-a0b3-c0bdc7c49d00>
- [31] Engelhardt, M. D., & Morovat, M. A. (2022). Directions in structural-fire safety design for steel buildings. Japan Architectural Review, 5(1), 20-31. <https://onlinelibrary.wiley.com/doi/abs/10.1002/2475-8876.12250>
- [32] Fernando, A. E. (2000). Modelling of fire spread and the growth of fire in buildings using computational fluid dynamics (Doctoral dissertation, Victoria University of Technology). <https://vuir.vu.edu.au/15593/>
- [33] Oluseyi, P. O., Akinbulire, T. O., Atunbi, C. T., & Akinyemi, M. I. (2019). Development of a model for mitigating fire spread in multi-storey buildings. Arid Zone Journal of Engineering, Technology and Environment, 15(2), 190-206.
- [34] Onyenobi, T. C., Hudson, J., & Ormerod, M. (2006). Onyenobi, T. C., Hudson, J., & Ormerod, M. (2009). A study of fire response to UK high-rise building morphology. Research Institute for the Built and Human Environment, University of Salford, 488-504 <https://www.irbnet.de/daten/iconda/CIB16585.pdf>
- [35] Almand, K. H. (2013). Structural fire resistance experimental research: priority needs of US industry. <https://books.google.com/books?hl=en&lr=&id=ae-7BAAAQBAJ&oi=fnd&pg=PP5&dq=Structural+Fire+Resistance+Experimental+Research&ots=ao22fFImWU&sig=AzfAmPxKNxYOneAxROJxAihORbM>
- [36] Sivasuriyan, A., Vijayan, D. S., Górski, W., Wodzyński, Ł., Vaverková, M. D., & Koda, E. (2021). Practical implementation of structural health monitoring in multi-story buildings. Buildings, 11(6), 263. <https://www.mdpi.com/2075-5309/11/6/263>
- [37] Temelli, U. E., Gultek, A. S., Uzunoglu, C. P., & Sayin, B. (2023). A multidisciplinary analysis of the fire propagation in the aspiration system of a building. Case Studies in Construction Materials, 19, e02375.
- [38] DeHaan, J. D. (2018). Computer fire models. In Emerging and Advanced Technologies in Diverse Forensic Sciences (pp. 149-180). Routledge. <https://www.taylorfrancis.com/chapters/edit/10.4324/9781315222752-9/computer-fire-models-john-dehaan>
- [39] Gargari, M. M. (2016). Development of novel computational simulation tools to capture the hysteretic response and failure of reinforced concrete structures under seismic loads. Virginia Polytechnic Institute and State University.
- [40] Mammoser Iii, J. H., & Battaglia, F. (2004). A computational study on the use of balconies to reduce flame spread in high-rise apartment fires. Fire safety journal, 39(4), 277-296. <https://www.sciencedirect.com/science/article/pii/S0379711203001504>
- [41] Nguyen, T. T. H. (2017). Composite framed buildings under fire-induced progressive collapse: computational analysis and design recommendations (Doctoral dissertation). <https://deepblue.lib.umich.edu/handle/2027.42/140923>
- [42] Wang, Y., Dong, Y. L., Li, B., & Zhou, G. C. (2013). A fire test on continuous reinforced concrete slabs in a full-scale multi-story steel-framed building. Fire Safety Journal, 61, 232-242. <https://www.sciencedirect.com/science/article/pii/S0379711213001252>
- [43] Zhong, G., Zhai, G., & Chen, W. (2023). Evacuation simulation of multi-story buildings during earthquakes based on improved cellular automata model. Journal of Asian Architecture and Building Engineering, 22(2), 1007-1027. <https://www.tandfonline.com/doi/abs/10.1080/13467581.2022.2070491>
- [44] Abdel, R. S. E., Ahmed, M. M., & Alazrak, T. M. (2015). Evaluation of Soil–foundation-structure Interaction Effects on Seismic Response Demands of Multi-story MRF Buildings on Raft Foundations. <https://www.sid.ir/paper/319788/fa>
- Kagitin, O., Veselivskiy, R., Havryts, A., Ballo, Y., Yakovchuk, R., & Kovalyshyn, B. (2024). Determining the influence of facade parameters and the width of a fire-proof eaves on preventing the spread of fire through external vertical structures of buildings. <https://sci.lubgd.edu.ua/jspui/handle/123456789/13586>