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Fire Safety in Buildings: Challenges and Opportunities for the Performance-Based Approach in Brazil

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Abstract. Throughout history, significant events like the Great Fire of London and the September 11 attacks have exposed weaknesses in fire protection regulations, leading to new rules that are often reactive. While these regulations enhance safety, they do not prevent initial incidents, highlighting the need for proactive strategies, particularly in complex buildings. A performance-based approach offers the flexibility to meet architectural demands, improve safety, reduce costs, and support both new constructions and retrofits. This method compares safe evacuation time with the structural failure time, prioritizing life protection. In Brazil, fire prevention approvals primarily rely on prescriptive methods. Limited national research and a lack of specific regulations hinder the adoption of performance-based design, despite the existence of established international guidelines. Although well-established international guidelines are in place, their implementation in Brazil faces challenges related to varying climatic conditions, locally available materials, occupancy patterns, and other regional factors. Furthermore, obstacles such as limited technical knowledge, a lack of normative guidelines, and high initial costs discourage clients from adopting these strategies. This work aims to discuss the challenges faced in Brazil regarding the implementation of this method, as well as the available opportunities, demonstrating how realistic fire event simulations can provide benefits within the Brazilian context.

Keywords: Fire; challenges; performance-based design; realistic simulation.

1 Introduction

Fire safety in buildings is essential for safeguarding lives and property. However, traditional technical standards and regulations often lag behind emerging architectural challenges. Consequently, continuous assessment and revision of fire safety measures are necessary to effectively address evolving risks and ensure adequate protection.

Several authors have linked major disasters to the development of codes and regulations. For example, Luo *et al.* [1] demonstrated that the Great Fire of London influenced the establishment of minimum distances between buildings and public streets. In another instance, Nunes [2] observed that, following the September 11 disaster, practices were implemented to prevent structural collapse. Likewise, Tavares [3] cites the Andraus and Joelma building fires in São Paulo, which led to changes in the legislation then in force. Together, these cases illustrate that analyzing past fires is crucial for identifying failures that contributed to disasters, enabling the revision of standards and the implementation of necessary improvements.

Although analysis of previous disasters contributes to the development of future regulations, this approach does not prevent initial damage, especially in buildings with complex or unconventional designs. The growing number of innovative structures highlights the limitations of standardized, prescriptive safety methods and

indicates the need for customized fire safety strategies.

Tavares [3] emphasizes that fire protection is necessary even in situations without fatalities or injuries, as fires can cause numerous direct and indirect losses, including the destruction of buildings, disruption of transportation systems, community stress, and even damage to a region's image, which can affect tourism.

Given these challenges, Duarte *et al.* [4] argue that fire safety requires an integrated, case-by-case approach. Advances in engineering and evolving construction practices necessitate innovative and flexible strategies that account for the distinct risks associated with each building.

Prescriptive methods frequently fail to address complex scenarios and atypical building designs. Consequently, a flexible approach is needed to evaluate the unique attributes of each project. The performance-based design (PBD) method offers a robust alternative for developing fire protection strategies suitable for a wide range of building types.

2 Performance-Based Design Applied to Fire Safety

To adapt fire protection to all types of buildings, it is essential to adopt the Performance-Based Design (PBD) method for fire safety. As highlighted by Rodrigues [5], PBD allows for precise analysis by considering all the specific characteristics of the building in question, including fire protection systems and evacuation strategies. In this way, it is possible to determine whether the performance achieved is sufficient to mitigate the risks, offering designers greater freedom to explore different strategies and technologies to meet the pre-established performance criteria, without being restricted to rigid prescriptive requirements.

The performance-based method becomes especially relevant as it enables structural engineers to quantify the safety of structures in projects for which no prescriptive standards exist. Gernay [6] emphasizes that, in existing buildings and historical heritage sites, it is even possible to control the mode of failure and structural stability during a fire, through designs adapted to their specific characteristics.

This is particularly important considering that each building presents its own challenges, some of which are more complex. For instance, megastructures often require evacuation times that approach the structural fire resistance time. This situation is critical because if the structure fails to withstand the thermal load for the duration necessary to ensure safe evacuation, the risk of collapse with casualties increases substantially, as exemplified by the case of the World Trade Center, cited by Duarte *et al.* [4].

To minimize these risks in mega-buildings, it is often necessary to adopt measures such as pressurized stairwells, emergency elevators, and refuge areas, as mentioned by Duarte *et al.* [4]. However, the effectiveness of these strategies depends on a careful analysis of their practical feasibility in emergency situations. This includes verifying whether occupants are familiar with escape routes, know how to use them, and understand how to act correctly in the event of a fire. The more sophisticated the evacuation strategy, the greater the need for training and preparation of the population to ensure that procedures are properly followed and risks to life are reduced.

Even a well-designed project can lose its effectiveness if users are unaware of how it functions, potentially resulting in significant human and material losses. In cases where the strategies heavily depend on human behavior, it is often important to assess the need to ensure that the structure has sufficient resistance to withstand the time required for evacuation, even if the intended solution fails (as an additional safety measure). Furthermore, it is recommended to integrate systems capable of mitigating risks to the health and lives of occupants, such as smoke control, efficient emergency signage, and redundancy in safety systems.

To ensure that these strategies and systems are effective in emergency situations, it is essential to predict the behavior of both fire and structure during a fire event. Within this context, the complexity of conducting realistic simulations becomes evident.

2.1 Complexity of Realistic Fire Simulation

In this context, it becomes evident that, although the performance-based method offers significant potential, its application is inherently complex and necessitates computational simulations to predict fire behavior and, consequently, determine the most appropriate design strategy.

Unlike the prescriptive method, which is simpler to apply, Engelhardt and Morovat [7] emphasize that

realistic fire modeling involves numerous interdependent parameters. It is necessary to consider aspects such as radiative and convective heat transfer from hot gases to the surfaces of structural elements, which allows for accurate evaluation of thermal exchange through convection. Based on the resulting elevated temperatures, it then becomes possible to calculate the structural response in conjunction with the applied loads.

The application of PBD enables a more detailed and realistic assessment of how a building behaves during a fire event, potentially leading to more effective and economically viable solutions. However, for the method to be effective, it is essential that computational analyses be conducted rigorously and grounded in a deep understanding of the thermomechanical processes that affect structures exposed to high temperatures. In this context, Stochino *et al.* [8] emphasize that fire exposure analysis allows for the accurate reconstruction of the temperature–time relationship, which constitutes a fundamental input for subsequent structural response assessment.

In realistic simulations, all parameters must be carefully considered to faithfully represent behavior under fire conditions—for example, the location of fuel and ventilation conditions. The size of openings, as well as their state (open or closed), directly affects the development of fire.

A key aspect is the assessment of the temperature gradient reached within the structure. Based on thermal analysis, it is also possible to conduct structural analysis at a global level, as noted by Gernay [6]. This is important because, as Júnior [9] warns, neglecting the loads transferred by adjacent elements in real fire scenarios can result in premature failure of the component under consideration. Conversely, global analysis may reveal the presence of the tensile membrane effect, which contributes to favorable structural performance in certain situations where collapse is avoided, as pointed out by Engelhardt and Morovat [7].

Thus, in addition to contributing to safety during the fire event itself, this methodology proves extremely useful for supporting post-incident decision-making, helping to determine whether to repair, reinforce, or demolish affected buildings.

To illustrate, consider a large, non-compartmentalized building with a length of 12 meters. Under the prescriptive method, it is assumed that the entire compartment reaches a uniform temperature, regardless of its geometry. All structural members are subjected to identical thermal exposure. Therefore, standardized fire resistance tables are used to define the required withstand duration for the entire structure. In contrast, performance-based method modeling in ANSYS accounts for factors such as radiative and convective heat transfer, the size and location of openings, air inflow and outflow, and the distribution of combustible materials. This approach demonstrates that fire development is strongly influenced by these variables. Analysis of thermal gradients within the structure (Figure 1) reveals a response that diverges markedly from prescriptive predictions. It also identifies regions most severely affected by fire exposure. Realistic simulation leads to more efficient structural design and potential cost savings for building owners.

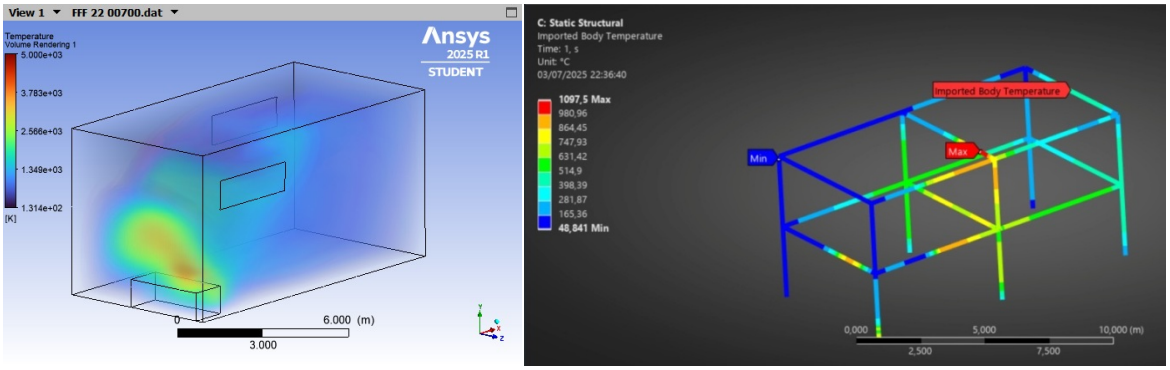


Figure 1. Fire development and application of thermal gradients on the structure.

Thus, it is confirmed that by performing realistic simulations—such as in buildings with large, non-compartmentalized spans, where fire behavior differs significantly from what is predicted by prescriptive codes—it is possible to achieve significant benefits. Among these are the reduction of protective material required during construction and the identification of structurally more vulnerable points, allowing for preventive reinforcement, as occurred in a case reported by Jokinen *et al.* [10] in Finland.

Furthermore, in post-fire scenarios, this type of analysis enables the identification of the most affected areas, guiding decisions regarding the feasibility of reusing the structure. Examples of such applications are described by Blanc [11] in a case study conducted in Andorra, and by Clifton *et al.* [12] in New Zealand.

These case studies underscore the potential of the performance-based method to deliver more precise solutions anchored in structural safety. In light of this potential, it is pertinent to examine both the opportunities afforded by PBD and the challenges inherent to its implementation.

2.2 Opportunities and challenges of the performance-based design method

Gernay [6] mentions several opportunities within the performance-based design (PBD) method, including advances in computational modeling, the evolution of element-level design, the use of stochastic modeling and probabilistic design, and the incorporation of artificial intelligence.

Regarding performance and artificial intelligence, Naser *et al.* [13] highlight ongoing studies in areas such as smoke control, intelligent fire detection and evacuation systems, and surrogate modeling techniques for evaluating fire response.

Despite these opportunities, analyzing fire behavior and structural response remains highly complex, primarily due to the integration of various disciplines, particularly thermal and structural analysis. This complexity stems from the need for precise data on material properties, physical and chemical processes, climatic conditions, and human behavior. These variables and their uncertainties make model validation particularly challenging.

Furthermore, the perception of risk and acceptable levels of structural performance remains inherently subjective for designers. This subjectivity can lead to discrepancies between the responsible engineer's understanding and that of the project evaluator. Currently, there is no consensus on how to select representative scenarios for structural fire analysis, as these decisions ultimately rely on the designer's professional judgment.

Consequently, given the architectural diversity, the specific requirements of each project, and the unique characteristics of each built environment, no guideline —current or prospective—can fully encompass all potential application scenarios or entirely anticipate future advances in fire safety engineering. This underscores the ongoing need for research and detailed, case-specific analysis.

2.3 Barriers to the Advancement of Structural Fire Safety in Brazil

In this context, one of the main barriers to the advancement of structural fire safety in Brazil is the absence of specific guidelines for addressing fire in design projects.

Current simulation limitations are associated with the high variability of the conditions involved, including material behavior, ventilation (whether through open, closed, or broken windows), environmental and climatic factors such as wind direction and speed, as well as air humidity. The difficulty of conducting full-scale experimental validations—due to high costs and the scarcity of specialized facilities—represents yet another obstacle to progress in the field.

The lack of specific data for Brazilian conditions—such as thermal properties of local materials, population evacuation behavior, fire growth rates, among other essential parameters for simulation—further hampers the adoption of performance-based methodologies. Additionally, limited technical familiarity with computational tools, such as FDS software, restricts the use of these solutions in the country.

Another relevant factor is the high computational cost of simulations, which can significantly increase the initial project cost, leading clients to resist adopting this approach.

This reality highlights the shortage of specialists in fire safety engineering and the limited understanding among structural engineers of the specificities of this methodology. The lack of knowledge and familiarity with the performance-based method also contributes to resistance from regulatory agencies when reviewing projects that depart from the traditional prescriptive model.

Moreover, this same lack of understanding can compromise the correct interpretation and application of simulation results, undermining the effectiveness of the solution and, consequently, the safety of the structure.

Despite these challenges, performance-based design (PBD) has shown promising results in the contexts where it has been implemented. It represents a vast area with significant development potential. The method

demands qualified professionals with in-depth technical knowledge, as their decisions directly impact safety, architectural design freedom, and even carbon emissions reduction.

Its application can drive the optimization, innovation, and evolution of structural systems, enabling the use of new materials and contributing to the response to climate emergencies. However, given the higher upfront costs associated with projects developed under this approach, implementing pilot projects in Brazil is essential. These studies would allow the practical demonstration of the benefits of PBD—both in terms of structural performance and potential cost reductions compared to the prescriptive model—thereby encouraging owners and investors to adopt this solution.

Additionally, the development and dissemination of model projects aimed at engineers, including fire and structural performance simulations and analyses, would be of great value for consolidating the methodology in the country. Such technical references provide essential support for conducting this type of project in a safe, realistic, and efficient manner, representing a fundamental step toward its widespread adoption in the national context.

3 Conclusions

In light of the above, it can be concluded that to enable the expansion of the performance-based design (PBD) method in Brazil, it is essential to invest in professional training, encourage national scientific production on the subject, develop technical guidelines tailored to the Brazilian context, and implement demonstration projects. These actions would not only highlight the practical feasibility and benefits of PBD but also provide a solid foundation for its proper application by professionals in the field. In this way, it will be possible to gradually consolidate the use of performance-based design reliably, aligned with the contemporary needs of the Brazilian construction industry.

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