This is a preprint draft. The published article can be found at: https://doi.org/10.1108/JSFE-01-2023-0002.

Please cite this paper as:
Craig D., Naser M.Z., (2023). "A Primer and Success Stories on Performance-based Fire Design of Structures." *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

A Primer and Success Stories on Performance-based Fire Design of Structures

Craig D., Naser M.Z.
School of Civil and Environmental Engineering & Earth Science (SCEEES), Clemson University,
Clemson, SC 29634, USA
E-mail: dcraig3@g.clemson.edu, E-mail: mznaser@clemson.edu, Website: www.mznaser.com

Abstract

Purpose

The extreme nature of fire makes structural fire engineering unique in that the load actions dictating design are intense and not geographically nor seasonally bound. Simply, fire can break out anywhere, at any time, and for any number of reasons. Despite the apparent need, the fire design of structures still relies on expensive fire tests, complex finite element simulations, and outdated procedures with little room for innovation.

Design/methodology/approach

This primer highlights the latest state of the art in this area with regard to performance-based design in fire structural engineering. In addition, this short review also presents a series of examples of successful implementation of performance-based fire design of structures from around the world.

Findings

A comparison between global efforts clearly shows the advances put forth by European and Oceanian efforts as opposed to the rest of the world. In addition, it can be clearly seen that most performance-based fire designs are related to steel and composite structures.

Originality

In one study, this paper presents a concise and global view to performance-based fire design of structures from success stories from around the world.

Keywords: Building codes; Performance-based fire design; Structural fire engineering.

Introduction

Over the past decades, fire statistics have improved, marking a 42% decrease in total deaths from 1980; yet the same statistics continue to show the adverse impact of fire on our communities. For example, according to the National Fire Protection Agency (NFPA), in 2021, local fire departments in the United States responded to calls for approximately 1.35 million fires [1]. These fires led to 3,800 civilian deaths and 14,700 injuries, not to mention roughly $15.9 billion worth of property damage. Despite only 36% of those fires taking place in structures, they accounted for 79% of civilian deaths and 80% of property damages for the year, a seemingly disproportionate amount.

The volatile nature of fire and its dependency upon its surroundings' conditions to determine its key characteristics make fire a challenging medium to predict and quantify [2]. The direct application of experimental fire tests requires creating standard structural tests under elevated temperatures, which in turn requires sophisticated equipment **Error!**

Please cite this paper as:
Craig D., Naser M.Z., (2023). "A Primer and Success Stories on Performance-based Fire Design of Structures." *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

Reference source not found.. This limits access to such tests, both because they are expensive and because it is specialized. On the other hand, the finite element models used to predict the behavior of fire-exposed structures can get complex, as they require much theoretical knowledge of the software's inner workings to accurately represent the physical systems. Unlike the above, this limitation can be overcome affordably.

Regarding codal provisions and procedures, most building codes rely on the more traditional, conservative prescriptive approach to fire resistance design and analysis [3]. This approach builds on the results from standardized tests. The more modern approach is the performance-based design approach. This approach allows the engineer some flexibility in design as long as adequate safety can be demonstrated. While progress is being made to shift some of the fire engineering design standards from a prescriptive to a performance-based approach, the latter is slow going and mainly utilized for specific cases rather than uniformity across the board.

Before diving into the performance-based fire design approach, it can be helpful to briefly go over the fundamental of structural and structural fire engineering. Structural engineering is the discipline within civil engineering responsible for designing and analyzing structural systems often seen, but not strictly limited to, buildings and bridges. These analyses are typically focused on stability and serviceability requirements. Stability references the strength of the system, while serviceability refers to the deformation, vibration, and other factors that influence how comfortable and safe the occupants feel while in the building.

While designing any structure, the final product must be suitable for a number of different conditions. Some conditions are dependent on the expected function and/or use of the building, mainly when considering the magnitude and type of loading that any given element in the building can be expected to encounter, along with a reasonable margin for error to account for material inconsistencies, future adaptability of the structure, and more general uncertainties of design. Other situations depend on extreme events, such as earthquakes, hurricanes, etc.

In the case of fire, the prescriptive approach specifies the fire resistance rating for individual structural elements based on a standard fire curve (ASTM E119) [4]. Figure 1 depicts the time-temperature curves for the standard fire used in ASTM E119, as well as its European counterpart, ISO 834 [5].

Please cite this paper as:
Craig D., Naser M.Z., (2023). “A Primer and Success Stories on Performance-based Fire Design of Structures.” *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

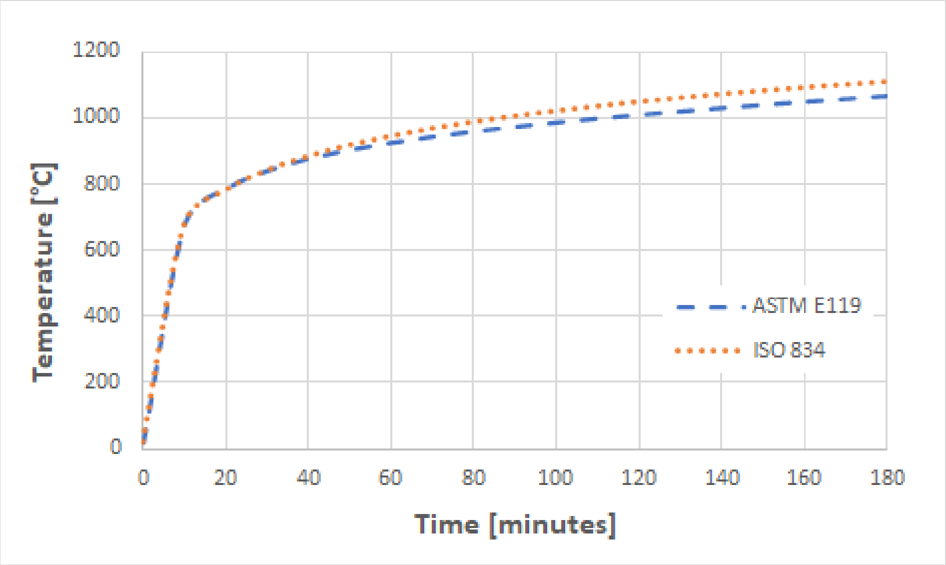

Figure 1: Standard fire design curves. (Source: Authors own work)

The prescriptive approach starts at the component level. Theoretically, if a building is composed of all elements up to a certain fire resistance rating, the requirement of which is based on the occupancy classification of the structure, then the building as a whole will stand up to that rating. Each element is given a conservative fire resistance rating based on previous broadly applicable research. These ratings are then simplified to hour(s) or fractions of hour(s) [6].

Ratings can be categorized into generic ratings, proprietary ratings, and approved calculation methods. Generic ratings refer to the fire resistance of popular construction materials, given mainly in building codes, such as concrete and structural steel. In contrast, proprietary ratings are based on the manufacturers of a building product as obtained from verified fire resistance tests completed to determine the rating used for each individual product. Approved calculation methods are a set of calculations the engineers can run to verify their proposed design work. This method is the least popular of the three, as it requires more labor on the part of the designing engineer.

Prescriptive methods, while simple to incorporate into design, can be a bit conservative and inconsistent. The fire rating system was created as a simplified, uniform procedure based on risk probabilities; this means the members' resistance is evaluated with standardized furnace test heating [7,8]. Since fire is such a variable event, the correlation between the behavior of the element under testing and under actual fire conditions it may face is bound to fluctuate wildly. That's not to mention that the entire fire-rating system was originally only supposed to apply to "common" buildings. This makes a bit of a grey area for buildings with unique geometry/features or mixed-use occupancy. Best practices developed over the years have given practicing engineers guidelines to minimize these

Please cite this paper as:
Craig D., Naser M.Z., (2023). "A Primer and Success Stories on Performance-based Fire Design of Structures." *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

concerns, but they have come into question in recent years, leading most countries to take on a more holistic approach to structural fire engineering.

Performance-based design is specific to each project; it sets specific performance goals for when the structure is exposed to elevated temperatures rather than regulating the construction side of matters. The performance-based approach thus allows for more innovation for the engineers, as it doesn't restrict the design process as long as adequate safety can be demonstrated, equal to that required of the prescriptive approach. When comparing performance metrics like deflection and thermal analysis for designs with each approach, the performance-based designs retained similar load-bearing capabilities to the prescriptive approach when taking into account the required fire-resistance rating [9].

While both approaches are theoretically similar in terms of performance metrics, the performance-based design "*offers more flexibility and potential cost reductions, owing to the fact that it takes into account system behavior and/or more realistic fire exposure*" [10]. This makes it desirable to clients, as it can be more efficient should it be completed correctly. Both approaches have their advantages; the performance-based approach can be adapted to unique designs or to cut costs without sacrificing safety, while the prescriptive approach has more conservative results and is typically easier for the engineer to implement.

The movement towards a more holistic approach to fire structural engineering can, in part, be attributed to the recent advancements in modeling and machine learning. With these new resources available, performance-based designs can be as efficient in terms of time or labor from the designated engineer as the prescriptive approach. As stated before, fire breakouts are not dependent upon a geographical location or seasonal timeline but very much upon the surrounding environment. The room's geometry, the materials in it, air ventilation, and more contribute to the fire behavior. To get an accurate representation of the effects of fire on a certain structure without the need for complex calculations and specialized education, software is commonly used. Basic software, like OZone, depicted in Figure 2 [11].

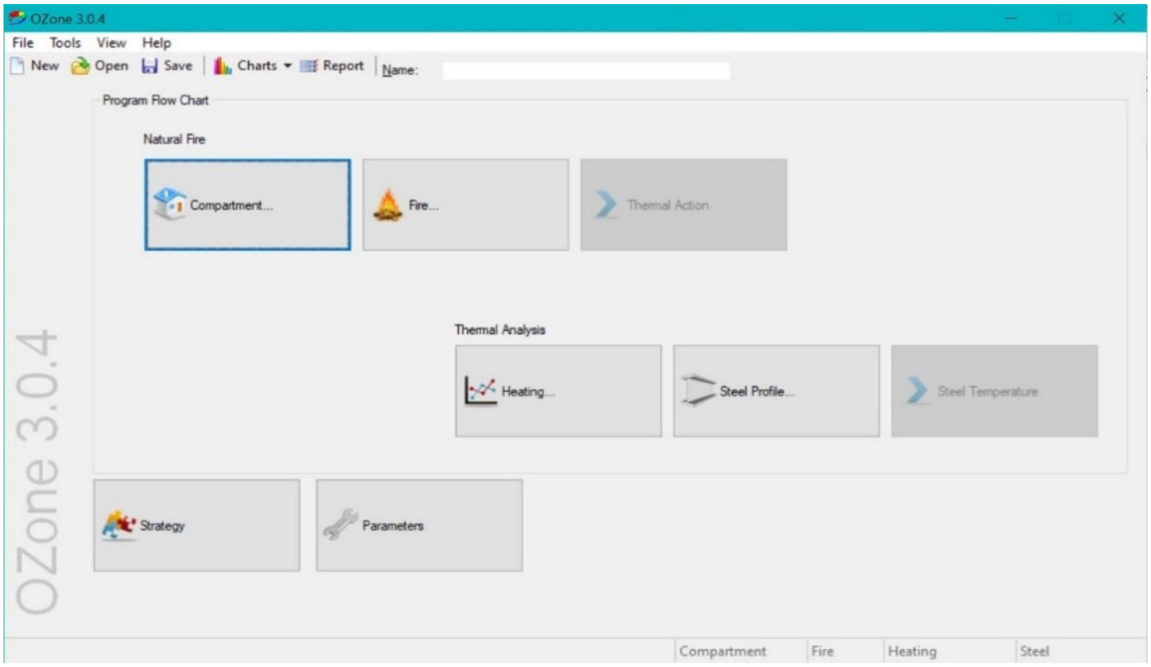

Figure 2: Sample of previously developed fire-resistance software, Ozone [11]. (Source: Ozone Software)

Depending on the sophistication of the modeling software, the models can also take into consideration additional properties such as thermal expansion, material nonlinearity, large deformations, and temperature-dependent properties. Similar software packages include SAFIR and FiRE (Fire, Radiation, and Egress Model).

With the complication of the software comes the addition of required knowledge for the engineer. The programs are completely dependent upon the inputs plugged into them – they don't have the judgment of an engineer to decide whether or not an answer seems reasonable, and thus cannot tell if a mistake was made in the creation of the model. For a model to have merit, the handling engineer should have at least a basic understanding of the program's internal workings, how varying each input affects the final results, and what physical phenomenon the input represents, both in magnitude and with appropriate units. Weighing this knowledge against the knowledge used to defend performance-based fire designs without the use of modeling software still makes it a significant improvement, but it needs to be said that the programs alone cannot act as justification for performance-based design; the engineer still bears all responsibility.

The current trend is that as more advancements are made in modeling and predictive programming capabilities (with the possible inclusion of machine learning [12]), more countries and their practicing engineers will shift toward performance-based design because of its increased efficiency and adaptability. This trend spills out into periphery topics; as the field begins to incorporate machine learning into its accepted practices, the same is to be expected.

Please cite this paper as:
Craig D., Naser M.Z., (2023). "A Primer and Success Stories on Performance-based Fire Design of Structures." *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

Given the above introduction, this short review hopes to present a primer into the latest state of the art on the front of performance-based design in fire structural engineering to promote the consideration of the latest advancements and success stories in the front of structural fire engineering applications.

A general view of the structural fire engineering practice

An engineer aims to identify fire risks involved in a project and design safeguards to mitigate the effects of fire, including preserving human life and, to a lesser degree, minimizing economic consequences. This responsibility typically has three goals: to prevent a fire, confine the fire to a certain region of the building (thus preventing spread), and extinguish the fire.

The prescriptive approach specifies the fire resistance rating for individual structural elements based on standard fire curves. In contrast, the performance-based design approach sets specific performance goals for when the structure is exposed to elevated temperatures rather than regulating the construction side of matters. Figure draws a comparison between these two approaches, as noted by England et al. [13]. Figure 4 further elaborates on the breakdown of the performance-based design approach.

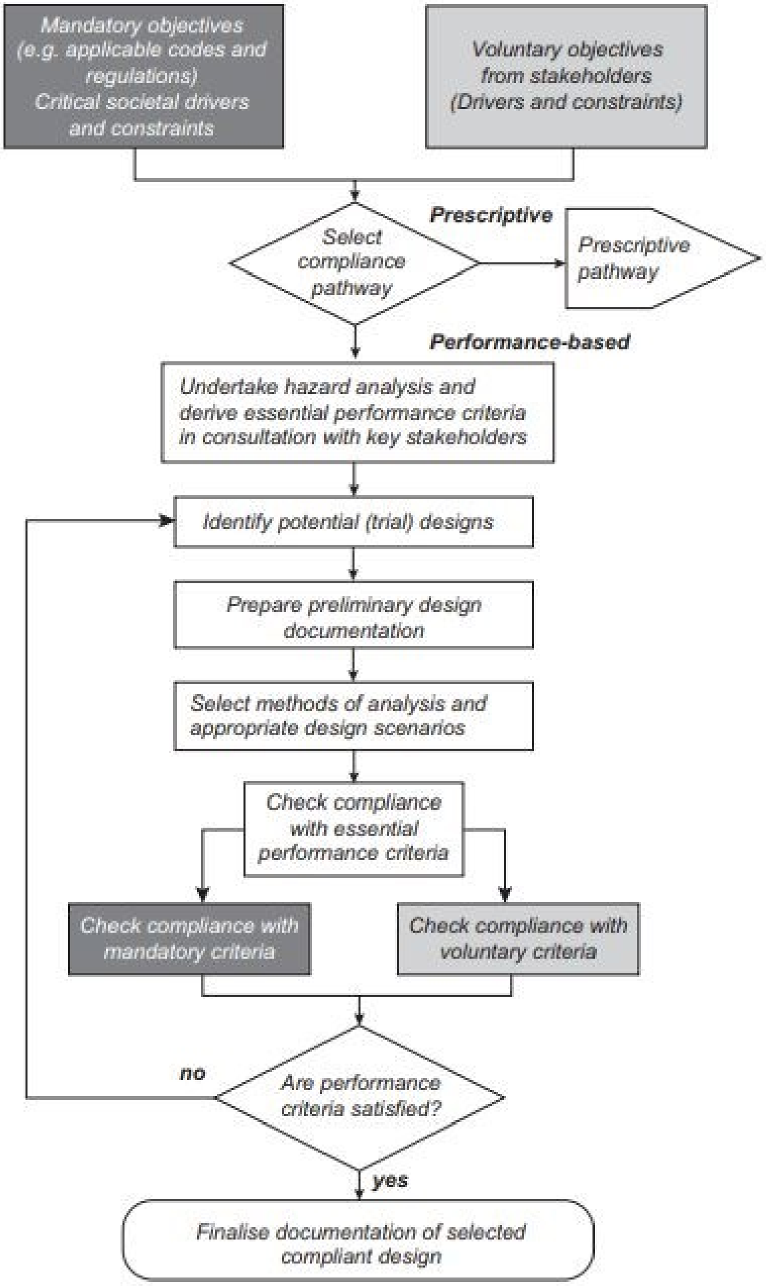

Figure 3: Overview of the structural fire engineering process. *Note*. Reprinted from Performance-based design and risk assessment in *Fire Safe Use of Wood in Buildings*, by England et al., 2022, p. 374. Copyright 2022 by CRC Press [13].

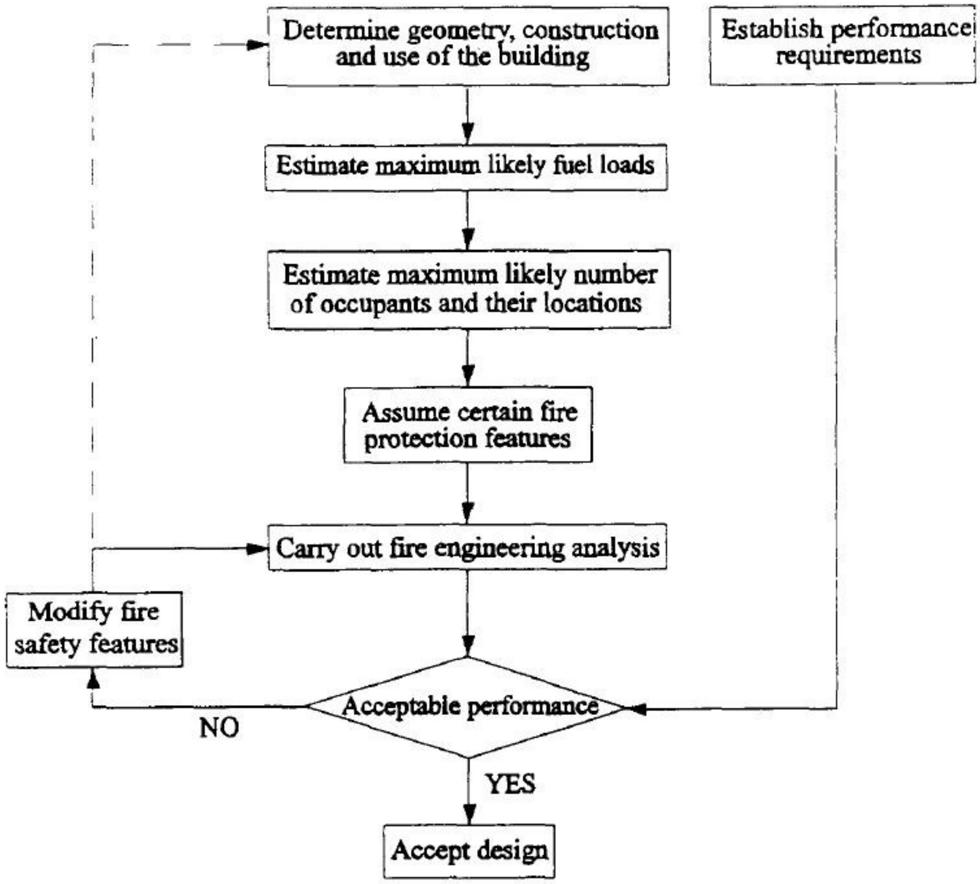

Figure 4: Outline of a performance-based fire engineering design procedure. *Note*. Reprinted from *Fire Engineering for a Performance Based Code*, by Andrew H. Buchanan, 1994, p. 6. Copyright 1994 by Elsevier Science Limited [14].

As more and more countries around the world make the transition to performance-based fire codes, some of such codes, standards, and guides can be found in Table 1.

Table 1: Limited catalog of performance-based design guides and standards.

Global
SFPE Handbook of Fire Protection Engineering [15]
ISO standards: 16732-1, 16733-1, 16733-2, & 23932-1 [16–18]
Europe
Eurocode 1 Actions on Structures – Part 1–2: General Actions – Actions on Structures Exposed to Fire [19]
Fire Safety Engineering – Comparative Method to Verify Fire Safety Design in Buildings. Inter-Nordic Technical Specification [20]
Fire Safety Engineering – Guide for Probabilistic Analysis for Verifying Fire Safety Design in Buildings. Inter-Nordic Technical Specification [21]
UK

Please cite this paper as:
Craig D., Naser M.Z., (2023). "A Primer and Success Stories on Performance-based Fire Design of Structures." *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

Application of Fire Safety Engineering Principles to the Design of Buildings – Code of Practice [22]
United States
Performance Code for Buildings and Facilities [23]
NFPA 5000 – Building Construction and Safety Code [24]
Australia
Handbook – Fire Safety Verification Method [25]
Australian Fire Engineering Guidelines [26]
New Zealand
Verification Method C/VM2, Framework for Fire Safety Design [27]
Fire Engineering Design Guide [28]

Note. Adapted from Performance-based design and risk assessment in *Fire Safe Use of Wood in Buildings*, by England et al., 2022, p. 378. Copyright 2022 by CRC Press [13].

Notable success stories and case studies

Performance-based design in itself is not a new concept. Its origins can be traced back all the way to 2250 BC to the Code of Hammurabi, which states, "*a house should not collapse and kill anybody*" [29]. The first time it appeared in building code was not until quite a bit later, in the last half of the 20th century. Its most widely accepted definition came from E.J. Gibson, a member of the International Council for Research and Innovation, who said, "*the performance approach is the practice of thinking and working in terms of ends rather than means. It is concerned with what a building or building product is required to do, and not with prescribing how it is to be constructed*" [30].

However, the implementation of performance-based design in the structural fire engineering field is a bit more recent. Most of its early uses in the field concerned evacuation protocols, smoke control, and exit designs. As technology has developed, its applications have broadened to include the structural design side of projects. As stated before, the level to which the performance-based approach is accepted in structural fire design is dependent upon the location both of the designing firm and of the project itself, in addition to the previous experience of the designing engineer. Therefore, this portion of the review will be organized based on the geographical location of the projects and codes that it evaluates.

Europe

Structural fire design was first incorporated in Eurocode EN 1991-1-2, released in 2002, identifying both prescriptive and performance-based approaches to be used by practicing engineers [19]. In the following years, the Eurocode practices were slowly adopted into national fire codes of European nations, beginning with the UK. These approaches are outlined in Figure .

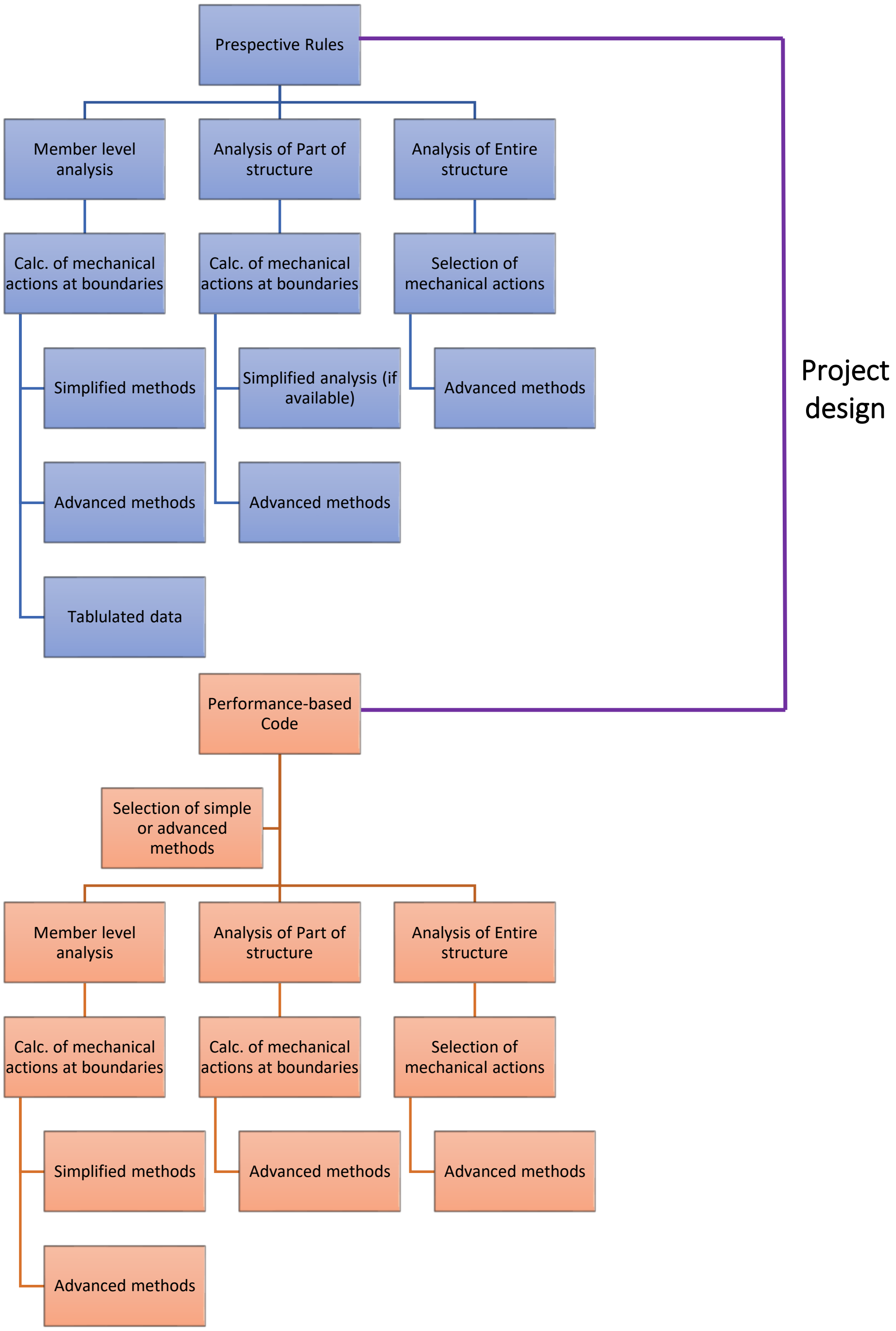

Figure 5: Alternative design procedure for Structural Fire design. *Note*. Reprinted from *EN 1991-1-1 General actions – Actions on structures exposed to fire*, by the European Union, 2001, p. 8. Copyright 2002 by European Committee for Standardization [19].

In one work, Heinisuo and Laasonen presented a case study on the Salmisaari Sports Centre, located in Helsinki, Finland [31]**Error! Reference source not found.**. At the time of this study, the performance-based design was already included in the national fire codes of the Czech Republic, UK, Finland, Hungary, and Italy. Performance-based fire design was used for the floor and roof trusses, with fire actions considered both for their intended occupancy and for special cases such as plastic-slide fires and stage fires (among five others).

Computer modeling was used to incorporate the effects of the rest of the structure, as performance-based design treats the structure as a whole, not as a sum of individual components. The software used was National Institute of Standards and Technology Fire Dynamics Simulator, based on computational fluid dynamics fundamentals to create a three-dimensional rectilinear grid congruent to most other finite element software [32]. The grid size was set with an upper limit of 200 mm in the area with elevated temperatures, based on a previous study by the same author [33]. At the end of the configuration, the simulation created temperature-time graphs for control points in each case of the evaluated fire actions, with an estimated 20% model and technical measurement uncertainty.

Petrini et al. conducted another case study on the Duomo of Modena Cathedral in Italy [34]. The cathedral presented a unique case, as it contained an impressive amount of valuable historical content while being quite an important building by itself but was also lacking a fire suppression system due to its historical construction. This case study was split into three sections: fire risk analysis, fire dynamics, and structural behavior. This involved the event-tree method, thermo-fluid dynamics models, and advanced nonlinear thermomechanical finite element models, informed by the guidelines of the Confirmation of Fire Protection Associations **Error! Reference source not found.**. These models used the same NIST FDS software, summarized in a group temperature-time and displacement-time graphs with the hope that the information they convey could help engineers work in conjunction with fire-fighters to establish a better-informed plan should a relevant incident ever occur.

Though more generalized geographically, Vacca et al. had an intriguing spin on the same line of research. Rather than compartment fires that originate in the structure through electrical mishaps or loose cigarettes, their work focused on the concern of wildfires with the increasing intensity of climate change [36]. The growing severity of the wildfires and the enlargement of the wildland-urban interface (WUI) settlements both posed a need for the adaptation of lower-level software to account for relevant variables like wind, inclined group surfaces, etc. Without these parameters taken into consideration, the software failed to accurately simulate and predict the effects of real fire exposure [37]**Error! Reference source not found.**. Headway was being made to rectify this, most of which again surrounded the NIST FDS, as it had already been heavily verified and accepted as commonplace practice in the area. These researchers offered procedures and considerations for uses of the computational fluid dynamics program to identify fire-vulnerable concern

Please cite this paper as:
Craig D., Naser M.Z., (2023). "A Primer and Success Stories on Performance-based Fire Design of Structures." *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

areas in the glazing systems, roofing, and gutters, and uneven building envelopes, all informed on the qualifiable knowledge gathered throughout the years from others on fires in the wildland-urban interface.

Asia

Moving on to Asia, Luo et al. put together a rather apt historical review of the role of performance-based fire engineering practices in China, focusing on the last three decades of advancements [38]. The trends in China mimicked that in the UK, discussed earlier in this chapter, rather well, with about a decade delay in governmental policy publication. Hong Kong appeared to be the trendsetter, with its policies influencing the mainland's industry best practices. Within that pattern, the Code of Practice for Fire Safety in Buildings in Hong Kong was released in 2011 [39], while a formal performance-based code still had not been released regarding China at the time of publication.

While progress in this specific area of fire engineering lagged a bit in the 1990s with its popularization in other parts of the world, the 2008 Beijing Olympics seemed to put it in overdrive [40]**Error! Reference source not found.**. While most of this study was focused on evacuation protocols and smoke management, structural components were considered both on an element-by-element basis (prescriptive) and for full-frame verification (performance-based), with respect to the "*credible worst fire scenarios rather than the standard fire curve*" used when following guidelines like the ISO or ASTM standards.

As stated previously, the Hong Kong Code of Practice for Fire Safety in Buildings was released in 2011. Lo et al. offered the unique perspective of engineers before the official addition of performance-based design to their respective governmental building codes [41]**Error! Reference source not found.**. Moreover, this piece was formed as a conceptual system dynamics model, focusing mainly on the qualitative process of structural fire and fire safety engineering rather than the quantitative modeling that has dominated the field in recent years. While it was helpful in allowing visualization of the relationships between components, it, more importantly, gave practicing engineers a place to start when the code was not yet up to the task, along with a reasonable expectation of how the approach was integrated into then-current building ordinances. After the model was presented, numerous simulation experiments were run to demonstrate how the model worked and to predict the effects on the field of fire engineering in general (in Hong Kong). The simulation produced many results, the most important of which was that the rate of fire-engineered design projects would increase (concerning the total projects approved) – precisely what occurred over the years following the publication of this paper.

Unlike other case studies, Rujin et al. attempted to fill a rather large hole in the existing literature by considering elevated temperatures' influence on bridges' structure [42]**Error! Reference source not found.**. While fire is not the most common method for causing failure in a bridge, vehicle-induced fire is a threat that continues to grow with the ever-increasing amount of transport in the world. Of course, full-scale fire tests are optimal in

Please cite this paper as:
Craig D., Naser M.Z., (2023). "A Primer and Success Stories on Performance-based Fire Design of Structures." *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

terms of learning applicable information, but they are extremely expensive and not to mention imperfect regarding environmental/safety concerns.

For more practical methods, Rujin et al. went back to the FDS, commonly referred to in Northern European industry, to stitch together previous, more narrowly focused research projects involved in solving this issue. After outlining a proposed method design framework using this software, they then went on to walk through a case study, assumed to be fictional as its location was not given, step-by-step to verify it provided all the information necessary for any practicing engineer. As a whole, the process seemed to be an adequate solution to bridge fire analysis.

Oceania

Turning the spotlight to Oceania, New Zealand first introduced performance-based structural fire design in their 1992 Building Regulations, where Clause C6 detailed the functional and performance requirements for structural stability [43]. These requirements dealt with the direct effects of the fire on the structural members and any effects resulting from the prevention/aftermath of the fires (weight of sprinkler systems, safe access for fire-fighters, etc.).

Buchanan introduced these new code developments and discussed the reactions to the changes directly after their implementation [14]. Buchanan stated, *"[a] holistic performance-based code require[s] a probabilistic performance statement for the whole building, including all aspects of the fire safety system*," which is reflected very prominently in the organization of the new fire code. Once the changes in the code had been discussed, as well as any background information necessary to understand its purpose, he then created a design guide for executing the new requirements. This guide covered fire safety and structural fire engineering, just like the code it is based upon, in the same order for ease of comprehension.

All calculations necessary were listed, as were recommendations on the resources with which to find them. As this was before the computational programs were created, these resources mainly consisted of well-known textbooks and handbooks written by fire engineering organizations. To go further, they also advocated for further education for design professionals on the matter, pointing to workshops and seminars from institutions all over the country. This researcher later developed a textbook about the same subject, aptly titled Fire Engineering Design Guide, around a decade later, once the performance-based design code was a bit more established [44]. This version included peer reviews, computer modeling, updates to the code (again), and more.

Akin to the FDS tool in Europe, New Zealand has its own tool titled B-RISK [45]. According to its official website, it was created to "*allow fire simulation results to be presented in a probabilistic form and allows the variability and uncertainty associated with the predictions of the fire environment to be quantified*" [46]**Error! Reference source not found.**. In preparation for its development, Baker et al. compared multiple user-input options for the design fire used in the software [47]. It was found that the design fire generator (created with B-RISK) and parametric heat release rate (calculated using statistics) curves were found to have similar results regarding the growth phase and fully developed phase with a few minor variations. Other details regarding the fire growth rate and location of burning objects were discussed, with the conclusion that the results gathered from the B-RISK simulation were very conservative when compared to the VM2 Verification Method in the 2012 New Zealand Building Code [27] and international research.

Pau et al. presented a case study analogous to the one described by Petrini et al. It contained the same considerations for heritage buildings, though this paper referred to the McDougall house in New Zealand rather than a church in Italy [48]. The building underwent multiple earthquakes in 2010 and 2011, leading to damage to the chimney and fireplace. The fire engineering design method used was taken from the same VM2 Verification Method in the 2012 New Zealand Building Code as the literature previously touched upon [27]**Error! Reference source not found.**. It also had an added layer of objectives, as the goal of the project was to conserve as much of the building's historical/heritage value as possible while still ensuring the safety of its occupants. This paper followed the same pattern of addressing fire safety engineering concerns (evacuation and ventilation) before moving on to the structural/construction side of matters (material choices, member repair). The approach used appeared to be a mixture of performance-based and prescriptive methods, as performance-based methods were used to qualitatively identify areas of concern, and prescriptive methods were used in the restoration of the fire resistance of the structural elements. The case study concluded with a table detailing the updates of all the fire protection systems; for structural elements, this included 30-minute rated plasterboard on the floors, ceilings, and walls. All structural steel was enclosed in the same material, achieving the same fire rating, which was found to be in compliance with New Zealand Building Code and thus acceptable to the engineers.

Before his work on the McDougall house case study, Fleishmann wrote his own piece, years prior, on the impact of the engineers' discretion in interpreting the qualitative guidance of performance-based design criteria [49]**Error! Reference source not found.**. Differences in these interpretations could lead to widely varying results and safety levels for structures that, on the outside, look like they should be fairly similar. While variation in the product itself was not necessarily bad, it could lead to some issues should careful consideration not be taken place.

In terms of safety, one of the more important conditions was that the available safe egress time (ASET) be larger than the required safe egress time (RSET) by a reasonable margin of error. The ASET was determined by computer modeling based on the performance criteria, predicting how the structure will behave, while the RSET was an estimate of how long people have to evacuate before the building is unsafe, therefore predicting how its occupants will behave. The issue was that these calculations relied on parameters that were not necessarily constant and/or provided, such as the design fire scenarios, design fires, and acceptance criteria. The researchers then concluded their remarks with a call for more

Please cite this paper as:
Craig D., Naser M.Z., (2023). “A Primer and Success Stories on Performance-based Fire Design of Structures.” *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

quantitative guidance for the aforementioned criteria, which was shortly answered with the VM2 Verification Method in hopes of providing the engineers in New Zealand with a more clear and more efficient method for performance-based structural fire design.

United States

Just because the performance-based design approach is not the most popular route for structural fire engineers in the United States does not mean that it's never done. The American Society of Civil Engineers first incorporated performance-based structural fire design into their code in 2016 [50] and established enough for the subsequent literature to have a decent amount of practical experience behind it [51]. Most of the literature focuses on concrete and steel structures, wherein steel tends to be a fairly uniform and predictable material.

Fischer et al. focused on compartment fires in medium-sized ten-story steel construction office buildings [9]. These buildings had their structural fire protection designed using the prescriptive method but then were analyzed with performance-based methods to see if any improvements could be made (and they could). The buildings were analyzed using nonlinear inelastic three-dimensional finite element models, with two phases: the first of which evaluated the heat transfer due to the emergence of the compartment fire and the second of which detailed the structural response following that heat transfer. These finite element models were developed through the ABAQUS software. The results from these models indicated that changing the elements that the fire protection was attached to increased the fire resistance of the buildings while improving their efficiency.

Alasiri et al. presented a very structure to the above researchers [52]. It was also a ten-story office building made with steel perimeter moment frames. This building, though, had the added concern of being in a high seismic region; therefore, the authors chose a very niche topic: assessing the impact of the damage caused by previous earthquakes on the behavior and stability of the structure during a fire. The simulated building was designed up to American standards, with the required fire resistance determined by the International Building Code [53]. The researchers then created performance-based parametric studies using ABAQUS of the simulated building being exposed to fire after having previously undergone eleven earthquakes. These parametric studies "*indicate[d] that partial or full collapse of the building structure [could] be prevented by sufficiently increasing the structural design (size) or fire protection (fireproofing thickness) of the critical gravity columns*," thus providing multiple practical options for the designated engineers.

While, as stated before, most of the established literature regarding performance-based design in the United States involved steel structures, there appears to be the beginning of a shift, or rather an expansion of subjects. Khorassani et al. completed a parametric study regarding performance-based structural fire design of composite floor systems [54]. This nine-story office building (with steel moment frames) was used to investigate the influence of many of the structural engineers' decisions regarding fire engineering, including "*modeling approach, fire curves, applied gravity loads, and hazard scenarios (fire-only vs.*

Please cite this paper as:
Craig D., Naser M.Z., (2023). “A Primer and Success Stories on Performance-based Fire Design of Structures.” *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

post-blast fire)." To do so, the MACS+ tool was utilized to simulate the composite slab under an ISO standard fire [55]. The performance-based design of the slab was found to be acceptable, able to temporarily withstand losing a column, allowing for complete evacuation of the building.

Comparisons of alternatives

While this paper provides a literature review and argument for the popularization of the performance-based design approach in structural fire engineering, it would be remiss not to recognize the alternative. More precisely, the next section of this review will cover comparisons between the performance-based design and prescriptive fire resistance methods.

Khorassani et al. composed a comparative study prior to the publication of the parametric composite floor analysis listed above [10]. In such a study, the same nine-story office building was used in this comparative study, though this paper was equally focused on evaluating both methods rather than trying to prove one is better. Thus, the same building was designed in two different ways: one following current prescriptive guidelines to get as close as possible to a real-life design in the US (spray fireproofing with each individual element acting alone [53]) and one that employed performance-based design to adjust reinforcement in the slab such that it achieves tensile membrane action.

The two structures were then modeled with a non-linear finite element program, SAFIR, which allowed for thermal analysis and subsequent transient structural analysis of building members at elevated temperatures [56]. These models were exposed to the standard ASTM E119 fire curve and a two-zone CFAST model that provided more adaptive and realistic results [57]. Both methods were found to be adequate when exposed to both kinds of fire, which showed that the performance-based approach was an acceptable alternative. Though, the labor and resources required to prove this fact call into question whether or not it is worth it for the practicing engineer to take it into consideration until performance-based design has more thorough guidelines and best practices available that are integrated into the national codes.

Sanctis et al. had a slightly different approach to comparing prescriptive and performance-based design; they compared them by proposing a method of quantifying the level of safety that each design would achieve [58]. This methodology could also be used to verify what is "equivalent" between the two design approaches. Mathematical models were created for each step of the methodology, describing anything from the limit state on the temperature domain to the influence of the fire brigade intervention. The level of safety for each method was found through a reliability analysis of these models, which was outlined in terms of fire ignition, the effect of the fire on the structure, and finally, structural failure. The reliability analysis found that the probability of failure using the prescriptive design approach depended on building properties, which makes sense as those are not considered in the guidelines themselves. The probability of failure when following the performance-based indicated it is more removed from building-specific properties.

While some of the literature discussed here attempts to be objective about the methods adopted by each nation, others make their opinion very clear. Such is the case with O'Loughlin and Lay [59]. Their problem lay in the 15-minute increments that the fire resistance of any given product is normally categorized as. As with any other procedure, the accuracy of the final results is only as strong as the accuracy of each step within the process. More eloquently put by Elms, "*the choice of level of detail in any part of an engineering procedure must to some extent be governed by the crudest part of that procedure*" **Error! Reference source not found.**.

As the field of engineering rapidly develops, as structural fire engineering has in the past few decades, the progress might not be uniform across the field, causing a weak link in the chain. Figure shows a rough interpretation by O'Loughlin and Lay [59] of the relative progression of different aspects involved in structural fire design.

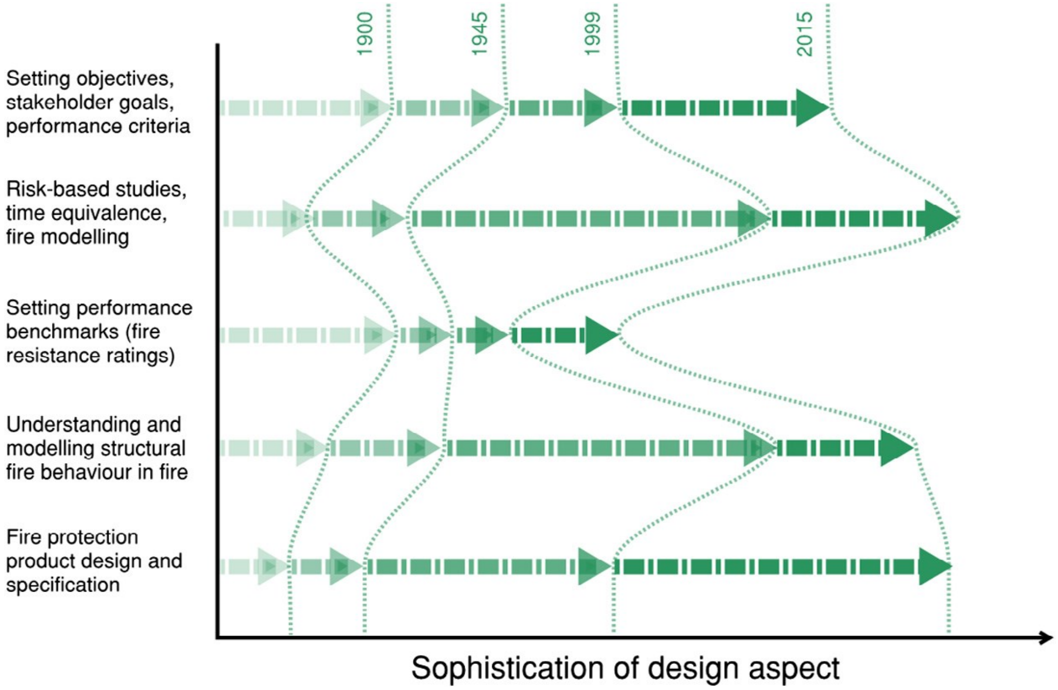

Figure 6: Relative progression of various facets involved in structural fire design. Note. Reprinted from Structural fire resistance: Rating system manifests crude, inconsistent design, by O'Loughlin and Lay, 2015, p. 39. Copyright 2019 by Elsevier Ltd [59].

Tavares attempted to do just that: influence code at a national level. This was done through a comparison of the two methods, done both in terms of objective economic impact and through a cultural lens specific to Brazil [60]. The first objective was completed fairly easily, with the advantages and disadvantages of both systems easily presented in charts. Based on the information, the prescriptive codes were nice in the way that fire safety engineers with high qualifications were not required, but there was a lack of flexibility and innovation to help reduce costs.

Please cite this paper as:
Craig D., Naser M.Z., (2023). "A Primer and Success Stories on Performance-based Fire Design of Structures." *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

Performance-based design was shown to have that flexibility and potential for economic efficiency, but it was difficult to quantify the criteria or validate the methodologies. After addressing how other countries shifted from prescriptive to performance-based codes, the focus shifted towards potential problems specific to Brazil, mainly the fear that the then-current fire codes were not well known or efficiently applied; therefore, how could any new ones be? Culturally, not much stock was put into fire risks, so while the long-term goals might've been to shift to performance-based design, there was much groundwork that needed to be laid before the country was ready for that. Perhaps this has changed in the years since the article was written, or perhaps not.

Meacham went one step beyond just comparing prescriptive regulations with performance-based; he added market-based into the mix [61]. Another unique note is that this paper was geared towards the influences of different types of regulations on buildings formed with modern methods of construction (MMC). This was in reference to buildings that are comprised of components prefabricated off-site, which makes construction move very quickly once the pieces have all been transported to their final location. This created issues specific to MMC, like the fact that the components are closed from view when inspected on-site, limiting what information can be gathered about their condition. Market-based regulations are similar to performance-based codes in that they are very objective based; the only difference is that the responsibility lies with the owner and/or developer rather than the involvement of any governing body. In the case of MMC, none of the three approaches were deemed to be admissible without caveats. Any objective-based code needed entire "systems" testing to be worthwhile, while the prescriptive design was based on standard fire tests that were not always applicable to the finished assemblies. Therefore, all methods are needed to find a way to adapt to complex systems as our industry and technology advance.

As one can imagine, there are numerous design parameters to be assessed for performance under various fire scenarios. One critical factor in performance-based fire design is the deflection limits of structural elements like horizontal members (i.e., slabs). In the event of a fire, extreme heat can cause the material of the slabs to deform, which can significantly affect the structure's stability and integrity. Thus, the performance of such members is to satisfy deflection limits (a measure that indicates how much a member can deform before it fails or becomes unsafe). Factors such as member thickness, material type, reinforcement ratio, and fire resistance rating are considered to determine the deflection limit.

Another crucial performance measure is the temperature within the member (i.e., reinforcement) during a fire. The temperature influences the properties such as strength, modulus of elasticity, and the overall ductility of the structure. High temperatures can degrade these properties and potentially cause structural failure. Further, the rate at which the temperature rises depends on factors like fire severity, the insulation/material cover thickness, and the properties of materials. The performance-based fire design aims to ensure that the rise in temperature does not reach the critical level where the strength is

Please cite this paper as:
Craig D., Naser M.Z., (2023). "A Primer and Success Stories on Performance-based Fire Design of Structures." *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

significantly reduced. Maintaining the temperature below this critical level helps preserve structural integrity and prevents the structure from collapsing under fire conditions.

Various building codes maintain limits that need to be satisfied to ensure proper fire performance. Such limits are a function of the construction material, element type, etc. While such limits were not included herein for brevity, we encourage interested readers and engineers to get acquainted with such limits based on the building codes/provisions they subscribe to.

Recent innovations and a look into the future

As all prevalent methods of structural fire design have been addressed, with a clear preference towards performance-based design, this section will focus on literature published within the last couple of years that have particularly inspired and innovative additions to research regarding performance-based structural fire design. This will provide a sense of where the application's current extent and where its future potential lies.

Gernay and Khorasani presented a very thorough archetype for computational analysis with their study of a steel-framed building with composite floor slabs [62]. The paper was similar to that with one of the same authors discussed before, namely the piece by Khorassani et al., with the exception of the multiple different models with increasingly larger scales and the iterative design process based on their analysis, which was the main draw of the paper. Their analysis began with an in-depth performance-based analysis of the structure after being exposed to elevated temperatures using computational modeling. Then, three different models were created: single slab, single slab with restraint, and full building. Each of the models was designed with the performance-based approach, as they "adopted a set of performance objectives for the structure based on a rigorous definition of fire hazard scenarios informed by probabilistic considerations…iteratively by acting on several design parameters affecting the thermal and structural response of the building." These designs were verified by the nonlinear finite element analysis, including scenarios of single- and multi-compartment fires and if a fire should break out following column loss. This analysis concluded that the full building model was most optimal, as it was the most realistic to be used in the case of extreme events like multi-compartment fires.

Danzi et al. recently released a new parametric method titled Fire Risk Assessment Method for Enterprises (FLAME) [63]. This risk assessment, or rather risk index, method combined the strategies from several established methods, including the Gretener method, the Fire Risk Assessment Method for Engineering (FRAME), the Building Fire Safety Evaluation Method (BFSEM), and the Dow Fire and Explosion Index [64]. This method was meant to be used as an alternative to complex computational fluid dynamics models briefly touched on before; performance-based design is not necessarily synonymous with simulated design, and this method intended to prove that. It went back to the fundamentals, basing its property risk evaluation tree structure on the NFPA Standard 550 Fire Safety Concept Tree [65]. Rather than organize the results in reference to time periods, in this method, "the fire risk [could] be described by a number of key attributes while considering the fire strategy in place and the facility conditions." The semi-quantitative parametric method was used in several case studies involving healthcare facilities, which found the method comparable to the Italian Fire Code prescriptive measures.

Siddiqui et al. had a different spin on integrating computer modeling into fire engineering, or rather the other way around [66]. As part of an international collaboration with BIM Standards Organization building SMART, a strategy was developed to incorporate fire safety engineering-specific information into the exchange of data involved in building information modeling (BIM). BIM creates virtual or simulated buildings with a combination of objects and information about those objects. Development of any given aspect of that information is given a level based on what information is available in the model and in what format it is given. The format controls what can be done with the information without the need for a third party or manual recreation of data by the engineer. The goal was to eventually get this information into a cloud-based environment where data could be called upon by any of the participants and easily integrated into other relevant programs. This paper outlined a three-step strategy to get to that goal, namely enhancing Industry Foundation Classes modeling specifications for fire safety engineering, implementing those specifications, then improving fire and evacuation modeling tools to support BIM [67,68] and machine learning [69,70] based.

Conclusions

The debate between prescriptive and performance-based approaches to structural fire design is intense. Prescriptive methods are easy to understand and implement, but they are restrictive in their uses and overly conservative in accounting for the variability in parameters that they do not take into consideration in their process. Performance-based methods allow for more flexibility and experimentation on the part of the engineer, permitting them to increase efficiency and minimize costs where possible, so long as it is verified that the safety of the occupants is not being sacrificed. That verification, however, tends to involve computational software capable of running complex calculations or professionals with specialized education, should the governmental codes not be sufficiently streamlined. These codes can often be left up to interpretation, as there can be qualitative benchmarks depending on the code's origin.

Despite the complications in the process, performance-based design has many benefits over the prescriptive approach, which will only continue to grow as the field evolves. This is evident in the way computational modeling and building information modeling (BIM), and machine learning (ML) has been integrated into structural fire analysis already. Such tools certainly widen the possibilities for the project, allowing for all sorts of material and geometrical configurations to be included.

Acknowledgment

We are grateful for the support of the National Concrete Masonry Association, Grant/Award Number: 2020.010, and the Society of Fire Protection Engineers (SFPE) Educational & Scientific Foundation.

References

[1] S. Hall, B. Evarts, Fire Loss in the United States During 2021, 2021. https://www.nfpa.org/~/media/fd0144a044c84fc5baf90c05c04890b7.ashx.

[2] V.K.R. Kodur, M. Garlock, N. Iwankiw, Structures in Fire: State-of-the-Art, Research and Training Needs, Fire Technol. 48 (2012) 825–39. https://doi.org/10.1007/s10694-011-0247-4.

[3] B. Meacham, R. Bowen, J. Traw, A. Moore, Performance-based building regulation: Current situation and future needs, Build. Res. Inf. (2005). https://doi.org/10.1080/09613210420000322780.

[4] ASTM E119, Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM International, West Conshohocken, PA, ASTM Int. West Conshohocken, PA. 552 (2016) 1–36. https://doi.org/10.1520/E0119-20.These.

[5] ISO 834-1999, Fire resistance tests — Elements of building construction, ISO, Int. Org. Stand., 1999.

[6] A.H. Buchanan, A.K. Abu, Fire Safety in Buildings, 2016. https://doi.org/10.1002/9781118700402.ch2.

[7] V. Kodur, M.Z. Naser, Structural Fire Engineering, 1st ed., McGraw Hill Professional, 2020.

[8] Z. Xiao, T.C. Ling, C.S. Poon, S.C. Kou, Q. Wang, R. Huang, Properties of partition wall blocks prepared with high percentages of recycled clay brick after exposure to elevated temperatures, Constr. Build. Mater. 49 (2013) 56–61. https://doi.org/10.1016/j.conbuildmat.2013.08.004.

[9] E.C. Fischer, A.H. Varma, A. Agarwal, Performance-Based Structural Fire Engineering of Steel Building Structures: Design-Basis Compartment Fires, J. Struct. Eng. (2019). https://doi.org/10.1061/(asce)st.1943-541x.0002370.

[10] N. Elhami-Khorasani, C. Fang, T. Gernay, Comparative fire analysis of steel-concrete composite buildings designed following performance-based and US prescriptive approaches, in: Appl. Fire Eng. - Proc. Int. Conf. Appl. Struct. Fire Eng. ASFE 2017, 2018. https://doi.org/10.1201/9781315107202-15.

[11] ArcelorMittal, Ozone (Version 3.0.4), 2018.

[12] M.Z. Naser, Mechanistically Informed Machine Learning and Artificial Intelligence in Fire Engineering and Sciences, Fire Technol. (2021) 1–44. https://doi.org/10.1007/s10694-020-01069-8.

[13] P. England, D. Barber, D. Brandon, C. Dagenais, G. De Sanctis, M. Klippel, D. Pau, C. Wade, Performance-based design and risk assessment, in: Fire Safe Use Wood Build., CRC Press, 2022. https://doi.org/10.1201/9781003190318-11.

[14] A.H. Buchanan, Fire engineering for a performance based code, Fire Saf. J. 23 (1994) 1–16. https://doi.org/10.1016/0379-7112(94)90058-2.

[15] M.J. Hurley, D. Gottuk, J.R. Hall, K. Harada, E. Kuligowski, M. Puchovsky, J. Torero, Jj.M. Watts, C. Wieczorek, SFPE handbook of fire protection engineering, fifth edition, 2016. https://doi.org/10.1007/978-1-4939-2565-0.

[16] ISO International Standardization Organization, ISO - ISO 23932-1:2018 - Fire safety engineering — General principles — Part 1: General, ISO Int. Stand. Organ. (2018). https://www.iso.org/standard/63933.html (accessed January 2, 2023).

[17] International Standardization Organization, ISO - ISO/TS 16733-2:2021 - Fire safety engineering — Selection of design fire scenarios and design fires — Part 2: Design fires, ISO - ISO/TS 16733-22021 . (2021). https://www.iso.org/standard/63142.html (accessed January 2, 2023).

[18] International Standardization Organization, ISO - ISO 16732-1:2012 - Fire safety engineering — Fire risk assessment — Part 1: General, ISO 16732-1. (2012). https://www.iso.org/standard/54789.html (accessed January 2, 2023).

[19] CEN, Eurocode 1: Actions on Structures–Part 1–2: General Actions–Actions on Structures Exposed to Fire, 2002.

[20] Nordic INSTA (InterNordicSTAndards) Technical Specification, INSTA 950 INSTA 950 INSTA 950 INSTA 950 Fire Safety Engineering-Comparative method to verify fire safety design in buildings, 2014.

[21] Nordic INSTA (InterNordicSTAndards) Standard, INSTA/TR 951:2019 Standard - Fire safety engineering - Guide for probabilistic analysis for verifying fire safety design in buildings SIS-INSTA/TR 951:2019 - Swedish Institute for Standards, SIS, 2019. https://www.sis.se/en/produkter/environment-health-protection-safety/protection-against-fire/general/ss-ss-insta-9512019/ (accessed January 2, 2023).

[22] BSI British Standards Institution, BS 7974:2019 Application of Fire Safety Engineering Principles to the Design of Buildings: Code of Practice, 2019. https://knowledge.bsigroup.com/products/application-of-fire-safety-engineering-principles-to-the-design-of-buildings-code-of-practice/standard (accessed January 2, 2023).

[23] ICC, Performance Code for Buildings and Facilities, ICC International Building Code Council, 2019.

[24] NFPA, NFPA 5000 Building construction and safety code, NFPA: National Fire Protection Association, 2018.

[25] ABCB, Handbook: Fire Safety Verification Method, Australian Building Codes

Board, 2021.

[26] BCB, Australian Fire Engineering Guidelines, Australian Building Codes Board, 2021.

[27] MBIE, C/VM2 verification method. In Framework for Fire Safety Design for New Zealand Building Code Clauses C1–C6 Protection from Fire (Including Amendment 6). Compliance Document, The Ministry of Business, Innovation and Employment, Wellington., 2020.

[28] M. Spearpoint, Fire Engineering Design Guide (3rd Edition), 2008.

[29] R. Harper, The Code of Hammurabi, University of Chicago Press, 1904.

[30] PBFPE, What is Performance-Based Design | Performance Based Fire, (2022). https://www.pbfpe.com/post/what-is-performance-based-design (accessed January 2, 2023).

[31] M. Heinisuo, M. Lassonen, J. Outinen, Fire resistance, Technical sheets, Urban habitat constructions under catastrophic events, in: Fire Des. Eur., Czech Technical University Press, 2010.

[32] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk, K. Overholt, Fire Dynamics Simulator technical reference guide, NIST Spec. Publ. 1018-1. US Dep. Commer. Natl. Inst. Stand. Technol. Gaithersburg, MD. (2016).

[33] H. M., L. M., H. T., B. T., Product Modeling in Fire Safety Concept, Effects of Grid Sizes and Obstacles to Steel Temperatures, in: IABSE Conference Information and Communication Technology (ICT) for Bridges, Buildings and Construction Practice, 2008.

[34] F. Petrini, A. Aguinagalde, F. Bontempi, Structural Fire Risk for Heritage Buildings by the Performance-Based Engineering Format, Int. J. Archit. Herit. (2022). https://doi.org/10.1080/15583058.2021.2022249.

[35] C.-E. (confederation of fire protection associations in Europe), Guideline No 30: Managing fire safety in historical buildings, (2013).

[36] P. Vacca, D. Caballero, E. Pastor, E. Planas, WUI fire risk mitigation in Europe: A performance-based design approach at home-owner level, J. Saf. Sci. Resil. (2020). https://doi.org/10.1016/j.jnlssr.2020.08.001.

[37] S.L. Manzello, R. Blanchi, M.J. Gollner, D. Gorham, S. McAllister, E. Pastor, E. Planas, P. Reszka, S. Suzuki, Summary of workshop large outdoor fires and the built environment, in: Fire Saf. J., 2018. https://doi.org/10.1016/j.firesaf.2018.07.002.

[38] M. Luo, X. Sun, S. Li, A Historical Review of Fire Engineering Practice and

Advances in China, Fire Technol. (2022) 1–45. https://doi.org/10.1007/S10694-022-01300-8/TABLES/4.

[39] B. Department, Code of Practice for Fire Safety in Buildings, Hong Kong SAR China, 2011.

[40] M. Luo, Fire Engineering Concepts, Arup J. 40 (2009).

[41] S.M. Lo, C.M. Zhao, M. Liu, A. Coping, A simulation model for studying the implementation of performance-based fire safety design in buildings, Autom. Constr. (2008). https://doi.org/10.1016/j.autcon.2008.02.014.

[42] R. Ma, C. Cui, M. Ma, A. Chen, Performance-based design of bridge structures under vehicle-induced fire accidents: Basic framework and a case study, Eng. Struct. (2019). https://doi.org/10.1016/j.engstruct.2019.109390.

[43] N.Z. Government, The Building Regulations, New Zealand, n.d.

[44] A.H. Buchanan, Fire Engineering Design Guide, University of Canterbury, n.d.

[45] Branz, B-RISK (Version 2019.03), (2019).

[46] C. Wade, G. Baker, K. Frank, R. Harrison, M. Spearpoint, B-RISK 2016 User Guide and Technical Manual, (2016).

[47] G. Baker, C. Wade, M. Spearpoint, C. Fleischmann, Developing probabilistic design fires for performance-based fire safety engineering, in: Procedia Eng., 2013. https://doi.org/10.1016/j.proeng.2013.08.109.

[48] D. Pau, C. Duncan, C. Fleischmann, Performance-based fire engineering design of a heritage building: McDougall house case study, Safety. (2019). https://doi.org/10.3390/safety5030045.

[49] C.M. Fleischmann, Is prescription the future of performance-based design?, in: Fire Saf. Sci., 2011. https://doi.org/10.3801/IAFSS.FSS.10-77.

[50] ASCE, Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-16), 2016.

[51] K.J. LaMalva, Structural Fire Engineering, American Society of Civil Engineers, 2018. https://doi.org/10.1061/9780784415047.

[52] M.R. Alasiri, R. Chicchi, A.H. Varma, Post-earthquake fire behavior and performance-based fire design of steel moment frame buildings, J. Constr. Steel Res. (2021). https://doi.org/10.1016/j.jcsr.2020.106442.

[53] IBC, International Building Code, 2018. https://codes.iccsafe.org/content/IBC2018?site_type=public.

[54] N. Elhami Khorasani, T. Gernay, C. Fang, Parametric Study for Performance-Based Fire Design of US Prototype Composite Floor Systems, J. Struct. Eng. (United States). (2019). https://doi.org/10.1061/(asce)st.1943-541x.0002315.

[55] O. Vassart, B. Zhao., MACS+ for membrane action of composite structures in case of fire. Design guide, (2012).

[56] J.J.M. Franssen, SAFIR: A thermal/structural program for modeling structures under fire, 2005.

[57] NIST, CFAST - Consolidated Model of Fire Growth and Smoke Transport (Version 7), (2016).

[58] G. De Sanctis, M.H. Faber, M. Fontana, Assessing the level of safety for performance based and prescriptive structural fire design of steel structures, in: Fire Saf. Sci., 2014. https://doi.org/10.3801/IAFSS.FSS.11-996.

[59] E. O'Loughlin, S. Lay, Structural fire resistance: Rating system manifests crude, inconsistent design, Case Stud. Fire Saf. (2015). https://doi.org/10.1016/j.csfs.2015.03.001.

[60] R.M. Tavares, An analysis of the fire safety codes in Brazil: Is the performance-based approach the best practice?, Fire Saf. J. (2009). https://doi.org/10.1016/j.firesaf.2009.03.005.

[61] B.J. Meacham, Fire performance and regulatory considerations with modern methods of construction, Build. Cities. 3 (2022) 464–487. https://doi.org/10.5334/BC.201/METRICS/.

[62] T. Gernay, N.E. Khorasani, Recommendations for performance-based fire design of composite steel buildings using computational analysis, J. Constr. Steel Res. (2020). https://doi.org/10.1016/j.jcsr.2019.105906.

[63] E. Danzi, L. Fiorentini, L. Marmo, A parametric fire risk assessment method supporting performance based approaches - Application to health-care facilities in northern Italy, Chem. Eng. Trans. (2017). https://doi.org/10.3303/CET1757051.

[64] Dow's Fire & Explosion Index Hazard Classification Guide, 1994. https://doi.org/10.1002/9780470938195.

[65] N.F.P. Association, NPFA 550 Guide to the Fire Safety Concepts, 2007.

[66] A.A. Siddiqui, J.A. Ewer, P.J. Lawrence, E.R. Galea, I.R. Frost, Building Information Modelling for performance-based Fire Safety Engineering analysis – A strategy for data sharing, J. Build. Eng. (2021). https://doi.org/10.1016/j.jobe.2021.102794.

[67] A. Davidson, J. Gales, BIM and Fire Safety Engineering – Overview of State of

Please cite this paper as:
Craig D., Naser M.Z., (2023). "A Primer and Success Stories on Performance-based Fire Design of Structures." *Journal of Structural Fire Engineering*. https://doi.org/10.1108/JSFE-01-2023-0002.

The Art, Int. J. High-Rise Build. (2021). https://doi.org/10.21022/IJHRB.2021.10.4.251.

[68] Q. Sun, Y. Turkan, A BIM-based simulation framework for fire safety management and investigation of the critical factors affecting human evacuation performance, Adv. Eng. Informatics. (2020). https://doi.org/10.1016/j.aei.2020.101093.

[69] X.Y. Zhao, J.X. Chen, B. Wu, An interpretable ensemble-learning-based open source model for evaluating the fire resistance of concrete-filled steel tubular columns, Eng. Struct. 270 (2022) 114886. https://doi.org/10.1016/J.ENGSTRUCT.2022.114886.

[70] M.Z. Naser, CLEMSON: An Automated Machine Learning (AutoML) Virtual Assistant for Accelerated, Simulation-free, Transparent, Reduced-order and Inference-based Reconstruction of Fire Response of Structural Members, ASCE Jounral Struct. Eng. (2022). https://doi.org/10.1061/(ASCE)ST.1943-541X.0003399.