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DESIGN CRITERIA AND LOADS

Performance Code Requirements in the Tall Building Environment

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Building risk and hazard from the threat of fire have been largely managed through prescriptive code requirements since the 1800's. Use of fire resistive materials, compartmentation features, and later, installation of automatic sprinkler systems and automatic fire alarm systems have worked together to make tall buildings extremely safe from the effects of a fire. Code prescribed mandates have worked very well to direct architects and engineers towards the necessary level of protection for the building occupants as well as the structure itself.

In the United States, many code enforcement jurisdictions have recognized the effectiveness of these integrated systems. While any number of anecdotal stories or narratives can be used to demonstrate this, perhaps the most compelling argument lies in the evacuation strategies associated with tall buildings. In the majority of circumstances, tall buildings have become a "defend in place occupancy" when the appropriate prescriptive systems and design features are present. In these environments, occupants are normally best served and protected by remaining in a given area provided they are not in close proximity to the initial fire.

The US code system is now moving to incorporate performance design options as an alternative to the long established, time tested, prescriptive design that has dominated fire protection codes and standards for so many years. A performance code, as defined by NFPA is essentially a document that states its goals and provides reference to some, but not all, of the approved methods to achieve those goals.

Numerous NFPA Technical Committees are moving to incorporate this design approach into the codes and standards that they author. This paper will provide a background on the unique issues surrounding high-rise fire protection and how the future solutions to this problem can potentially be handled through application of performance based design.

INTRODUCTION

The use of mandated and legally enforced prescriptive codes has been the primary method used in the US to provide minimum requirements for building design and construction. These codes, normally described as providing a minimum level of protection – to occupants, the structure and the contents in some cases – work to ensure that certain very broad goals are achieved, that buildings owners get what they pay for, and to some extent, to protect engineers and architects from litigation involving their design work.

The fire risk associated with high-rise buildings has been a concern to the fire community since these buildings emerged at the beginning of the century. The special code requirements for these structures reflect the fire experience in high-rise buildings and the need to provide adequate fire protection. The incorporation of performance based design options to the standard prescriptive code requirements is currently being undertaken by NFPA along with the U.S. code system. This paper will provide a background on the unique issues surrounding high-rise fire protection and how the future solutions to this problem can potentially be handled through application of performance based design.

A high-rise building, as defined by Section 3.3.25.6 of NFPA's *Life Safety Code*, 2000 edition is a building greater than 75 ft (23 m) in height where the building height is measured from the lowest level of fire department vehicle access to the floor of the highest occupiable story. However, different definitions may exist in local jurisdictions that may use height or number of stories for their defining criteria. In general, a high-rise structure is a building of seven stories or more. The national fire incident databases provide four categories of high-rise buildings: 7–12 stories, 13–24 stories, 25–49 stories, and 50 stories or more. The four property classes incorporated in high-rise buildings are office, hotel, apartment, and hospitals (or other care for sick facilities). The type of occupancy is important in determining the appropriate fire protection as different types of fires are likely to occur for each property class and the occupant characteristics are quite different for each building. The NFPA Fire Analysis Division utilizes these occupancy divisions and breakdowns to assist in their annual collection and data reports on the US fire problem.

Several key characteristics can be described for high-rise buildings that result in the need for specific fire protection engineering approaches to ensure the life safety of the occupants and the protection of property. The distinguishing features of tall buildings require different and additional design considerations than lower, more conventional buildings. Some of the major issues that influence the fire protection in high-rise buildings are fire department accessibility, egress systems, the effect of natural forces on a fire, increased occupant loads, multiple and mixed use occupancies, and the complexity of internal utility services.

TERMS AND DEFINITIONS

The following terms as used in this paper have the meanings as shown below:

Approved Method. Authoritative procedure used to develop proposed solutions. A more commonly used example of approved methods is contained within prescriptive documents.

Calculation Method.* A description of a system or phenomenon in terms of relationships among elements, permitting study of how some elements vary when other elements are changed. A calculation method normally consists of one or more mathematical relationships, permitting calculation of some elements based on their relationship(s) to other elements. Note that fire science and engineering use "model" as a synonym to calculation method but also for other concepts and elements such as scale models.

Computer Model. A calculation method that is packaged as computer software.

Fire Effects Model. A calculation method that incorporates engineering and scientific principles and applies them in a logical manner to determine possible consequences and extent of physical effects based on an externally specified fire, expressed as heat release rate as a function of time. (Typically referred to as a "fire model", even though it may not model combustion.)

Evacuation/Egress Model. A calculation method used to describe the behavior and movement of people during a fire situation. May be used in combination with a fire effects model to determine whether or not occupants safely escape from a building before being exposed to products of combustion.

Computer Fire Model. A calculation method that is packaged as computer software and used to predict fire behavior.

Design Team. Group of stakeholders including, but not limited to, representatives of the architect, client, and any and all pertinent engineers and other designers. A stakeholder is an individual, or representative of same, having an interest in the successful completion of a project.

Performance-Based Design Approach. A design process whose fire protection solutions are designed to achieve a specified goal for a specified use or application. This process allows performance-based documents to be implemented and ensures that their goals are met.

NOTE: The following describes a performance-based design approach:

a) Establish fire safety goals.
b) Evaluate the condition of the occupants, building contents, process equipment, or facility in question with regard to fire protection.
c) Establish performance objectives and performance criteria.
d) Identify potential hazards to be protected against.
e) Define appropriate scenarios.
f) Select suitable verification methods (e.g., fire models).
g) Develop trial solutions.
h) Assess proposed solution.
i) Document proposed solution along with supplementary information.
j) Obtain approval of the proposed solution.

Steps a) through f) are also part of the development of a performance-based code or standard. Only steps g) through j) are specific to performance-based design, where the intent is to find a solution for the project. Also, steps c), d), and e) are not necessarily intended to be sequential; they may in fact be concurrent. While the above is presented in a sequential order, the design approach does not necessarily need to begin with step a) and proceed consecutively through step j). Since different stakeholders (e.g., owner, designer, authorities) must be satisfied, some steps of this approach are iterative. Similarly, for performance-based document development, steps a) through e) may or may not be taken sequentially.

Performance-Based Document. A code, standard, or similar document that specifically states its fire safety goals and references approved methods that can be used to demonstrate compliance with its requirements. The document may be phrased as a method for quantifying equivalencies to an existing prescriptive-based document and/or it may identify one or more prescriptive documents as approved solutions. Furthermore, the document allows the use of all solutions that demonstrate compliance using approved methods.

NOTE: A performance-based document may also include separate prescriptive provisions as a parallel, independent approach to meet the performance-based goals and objectives.

Prescriptive-Based Document. A code or standard that prescribes fire protection for a generic use or application. Fire protection is achieved by specifying certain construction characteristics, limiting dimensions, or protection systems without providing a mechanism for how these requirements achieve a desired fire safety goal. Typically these documents do not state their fire safety goals.

NOTE: Many current NFPA codes and standards are not strictly performance-based or prescriptive-based: technically, they can be referred to as prescriptive documents containing some performance provisions. For example, a requirement for a one-hour door sets a measurable performance criterion, going beyond prescription of the door's construction, but does not link the criterion explicitly to a fire safety goal.

Proposed Solution. A fire protection system design intended to achieve the stated fire safety goals and which is expressed in terms that make it possible to assess whether the fire safety goals and objectives have been achieved. If models are used, then the proposed solution should also specify the models and input data employed.

Top-Down. One approach used to develop performance-based provisions. Using this approach, the goals and objectives are developed during document revision processing without consideration of any current prescriptive requirements: a "clean sheet of paper" approach. See "Bottom-up".

Verification. Confirmation that a proposed solution (i.e., candidate design) meets the established fire safety goals. Verification involves several steps. Verification confirms that the building is built as proposed to a design that will achieve the intended level of safety and that the building's ability to achieve the level of safety has been demonstrated by qualified people using the correct methods applied to the correct data.

HISTORY OF FIRE IN HIGH-RISE BUILDINGS

Tall building fires repeatedly show the importance of implementing the existing and proven fire protection technologies. In 1996, high-rise building fires in the US in all occupancies combined had 12,100 reported structure fires that resulted in 64 civilian deaths, 790 civilian injuries, and $69.1 million in direct property damage.

Fires in high-rise buildings are significant events in the fire protection engineering profession. Such fires have often resulted in changes to prescriptive code rules, and have provided the basis for improved technologies to deliver water supplies that are adequate to combat fires in the upper reaches of the building. Automatic sprinkler systems, standpipe systems, and fire alarm systems have all been tailored in their own way to properly function in the unique environment of the tall building. Retroactive automatic sprinkler system regulations have been passed in numerous states and cities in the US in recognition of the need to provide a needed level of protection.

The US, while perhaps having the greatest number of tall buildings in the world, shares in a worldwide fire history where fires in high-rise buildings have resulted in multiple fatalities to both civilians as well as fire suppression personnel.

Table 1 captures a small percentage of fatal fires in high-rise venues (NFPA, 1999).

Table 1 Fatal Fires in High-Rise Buildings.

Date	Building	Location	Number of Fatalities	Floor of Origin/ Total Height (Stories)
25 Mar 11	Asch Building	NY, NY	146	8/10
1 Aug 32	Ritz Tower	NY, NY	8	Sub-basement/42
5 June 46	Hotel Lasalle	Chicago, Il	61	1/22
28 June 63	Astoria Building	Rio De Janeiro, Brazil	7	14/22
7 Dec 67	Time-life	Paris, France	2	8/8
24 Jan 69	Hawthorne House	Chicago, Il	4	36/39
25 Dec 71	Tae Yon Kak Hotel	Seoul, Korea	163	2/21
23 July 73	Avianca Tower	Bogata, Colombia	4	13/36
1 Feb 74	Crefisual Bank Building (Joelma)	Sao Paulo, Brazil	179	12/25
21 Nov 80	Mgm Hotel	Las Vegas, NV	85	1/23
8 Feb 82	Hotel New Japan	Tokyo, Japan	32	9/10
5 Sept 86	Hotel	Kristianstead, Norway	14	1/13
31 Dec 86	Dupont Plaza Hotel	San Juan, Puerto Rico	96	1/20
23 Feb 91	Meridian Plaza	Philadelphia, Pa	3	22/38
20 Nov 96	Office	Hong Kong	40	Basement/16
23 Dec 98	West 60 Th. Street Towers	NY, NY	4	12/40

Some common factors contributing to significant losses in high-rise fires are listed below. These conditions can be eliminated from buildings with the use of adequate, prescriptive based fire protection criteria and performance-based design.

- Lack of automatic detection equipment
- Inadequate/locked/blocked exits
- Inadequately protected vertical and horizontal openings
- Lack of alarm system, poor accessibility of alarm system
- Inadequate water supply for the standpipe system
- Lack of compartmentation
- Lack of automatic sprinkler protection.

NFPA fire investigation reports issued on several of these fires including the ASCH, Hotel LaSalle, Crefisual, MGM Hotel, Dupont Plaza and Meridian Plaza fires could all be narrowed down to some combination of these seven conditions. There is nothing inherently dangerous about high-rise buildings from the point of fire protection and life safety. It is noted in the select cases shown, that several of these fires had their point of origin at or near the ground floor.

Prescriptive Code Provisions and Fire Protection

Building code, life safety code and fire prevention code regulation in the United States have largely grown out of insurance industry regulation and rules. For example, building construction features were managed so as to provide protection to the contents that may have been stored in a warehouse. Protection goals may have simply been to keep weather related events (rain, snow, excessive sun) from damaging or altering the stored content. Beyond weather related damage, damage from fire related events also became a subject of concern for the US insurance industry. In general terms, the initial concerns for such losses focused on the factory and warehouse environment. Single, large, unmanaged fires could easily destroy a building or complex, thereby rendering the local economy, local residents, and entire companies in dire straits.

In a series of related events, the widespread losses that occurred during large, massive, urban conflagrations in key developing cities, including Boston, Chicago, Baltimore and San Francisco, the larger issue of how a fire in one building or structure could impact on an adjacent building, structure, neighborhood, or entire city, soon became an issue for all codes to consider. Code prescribed rules of minimum separation distance to other properties, imposition of selected construction techniques and installation of automatic fire sprinkler systems in many buildings set the stage for formalized rules in codes, standards and even certain zoning regulations.

Multiple story buildings, designed to take advantage of the limited real estate, set back, user needs and space limitations normally found in urban centers, have proven to be an effective use and utilization of these conditions. Code development organizations and insurance interests while initially reluctant to embrace the concept of not only two story structures used to operate factories, had to be brought into the fold of accepting the ever increasing challenge of story 'creep', that is, engineering limitations on building materials and design techniques appeared to be the only forces curtailing the design of taller buildings. With time, these limitations were torn down, and more floors were built on.

Regulatory documents were expanded to require heavy timber construction techniques in certain multiple-story buildings (generally factory and warehouse buildings, five and fewer stories in height), and 'fire proof' construction (generally referred to as fire resistive construction) in buildings taller than five stories in height. In 1920, the US code system incorporated another prescriptive regulation for building construction, the height and area table. Height and area tables, still used in all of the major US codes, impart selected maximum building footprint areas, and maximum building heights, in both a number of stories as well as a vertical, linear dimension. Allowable heights and areas relate directly to allowable building construction types. These combinations are intuitive as fire resistive, building construction types are generally permitted to reach unlimited areas and unlimited heights given the presence of certain other design features. Conversely, selected types of wood construction receive severe limitations with respect to both height and area, even when other positive fire protection attributes are present.

Code regulation trends also started to move towards a method of protecting the occupants of these multiple story buildings. On March 25, 1911, the first documentation of a fire in a US high-rise building (as defined by today's standards) occurred in the 10 story ASCH building in New York City. The primary tenant of this building was the Triangle Shirtwaist Company. The 146 lives lost in this building marked the beginning of the need to control and provide select features that protected not just the building and contents, but also the occupants. This fire also was significant in that the strategies associated with fighting fires in taller buildings were brought to the forefront.

A MOVEMENT TOWARDS PERFORMANCE CODE REQUIREMENTS

A level of performance requirements in US codes and standards was present in certain regulatory standards at the turn of the century. As an example of this, the following statement concerning placement and positioning of automatic sprinklers in buildings is taken verbatim from the 1896 edition of NFPA 13, Standard for the Installation of Sprinkler Systems. “Sprinklers should be located so as to not be shielded by building construction features” (NFPA, 1896). In the 1999 edition of this standard, no less than seven pages of text and accompanying diagrams are necessary to detail how you can achieve the performance goal from the first edition of this standard. The US code system, at least as it relates to fire protection, has come full circle. Minimal, goal oriented text, has been expanded, detailed and otherwise revised to be as thorough as possible.

A new era of design challenges has opened the door to consider other than the tradition of strict, prescriptive approaches to fire protection. Highly specialized industrial facilities, large assembly occupancy buildings, extreme high-rise buildings, and the need to out do other building designs by doing more, doing better and completing projects on time and in a more economical way, have all contributed to the decision to introduce performance-based design. PB designs leverage the ability of engineers and architects to challenge the status quo. This option allows, as a minimum, the following elements to be considered: (NFPA, 2000a)

1. Allow code developers to quantify established prescriptive code requirements. Doing something the same way, for 20, or 30 or even 100 years may not necessarily be the best method or solution.
2. Permits designers to provide highly specialized and innovative designs for aesthetic and effect purposes.
3. Permits designers to filter out excessive or overly conservative design features that may not enhance occupant safety or building protection features.
4. Allow designers to explore techniques, methods and solutions not explicitly covered by the prescriptive regulation.
5. Allows end users (building owners and operators) to modify prescriptive code regulations to provide more than the minimum level of protection that is normally provided in codes and standards.

NFPA embarked on a program in 1995 to begin the development of a system where NFPA Technical Committees could begin establishment of a process to integrate a PB design option in the codes and standards developed in the NFPA code development system (NFOPA, 1995). The first document to complete this process was the 2000 edition of NFPA 101, Life Safety Code (NFPA, 2000; CTBUH, 1999). The process used to arrive at this point followed the outline of the 1995 white paper from the NFPA Board of Directors. In general terms, the method used was one of the top down approach as shown in Figure 1. Establishment of the goals of this particular code (which were actually first specifically refined in 1991) were used to build upon the line of attack to outline the relevant items that would have to be considered in order to arrive at a credible life safety design.

The goals and objectives established in this top down approach can be used to consider all manner of building hazards beyond life safety. For example, this model can be applied to a building's ability to withstand select environmental loads, seismic events, and fire events as they relate the functionality of the building following a severe fire event. In this process, design goals should be established by the legal equivalent of a code. The subset of objectives, established by the design team can establish the level of performance needed during and following the event. In terms of life safety only goals, the building performance criteria, and subsequent objectives, these elements may only have to allow for adequate time for building occupants to relocate to safe areas within the building, or to permit time for occupants to evacuate the building.

The tall building environment fully recognizes the benefit, and the normally accepted practice, of relocating occupants from the floor of origin to areas remote from the fire. This environment also recognizes the importance of maintaining structural integrity during a fire event, and in recognizing the need to complete repair and clean up as soon as possible so as to allow 'business continuity' to the extent possible. Beyond this, the potential for structural collapse during a fire event is intolerable given the likely impact on adjacent and neighboring properties. Objective based PB code designs should always consider the effects of a fire on not only the building of interest, but also on neighboring properties.

The core of arriving at the ability to provide a solution deemed to be acceptable by a governmental regulatory authority (this term is defined by NFPA as the Authority Having Jurisdiction-AHJ) is complex, thus PB designs are unlikely to be applied to typical design, or design build projects. While the NFPA PB Primer establishes the framework for the method to be followed, the collective opinions of the design team must be vetted, refined and codified in a manner such that everyone, including the AHJ, is able to defend the ultimate design solutions, and hence design options that are offered.

Verification of the applied design methods or solutions is expected to come forward in one of four ways, or more likely, some combination of these. The four basic verification methods include:

1. Deterministic. Based on mathematical equations to verify an assumption or phenomenon.
2. Probabilistic. Based on historical loss data.
3. Heuristic. Based on investigation of losses, general problem solving, and judgment.
4. Laboratory Tests. Based on scale tests of materials or assemblies.

While none of these methods should be favored in one manner or another, the use of deterministic and probabilistic methods are likely to have more credibility to obtain recognition of one acceptable solution over another acceptable solution. Deterministic methods encompass the relatively new (25 years) use of computer fire models (Society of Fire Protection Engineers, 1994). A variety of these models can be used to simulate fire growth characteristics, smoke movement and even evacuation and movement times for building occupants. Input for these models as well as interpretation of the output from such models must be carefully scrutinized. Subsets of this category include hand calculations, physics models (which is further divided into 3 categories), and evacuation models.

The subset of 'field models' under the physics model category is viewed by many as the most promising model for simulation of fire effects. This type of simulation evaluates a nearly infinite number of space or compartment volume units and is generally referred to as a computation fluid dynamics (CFD) model. CFD models, while requiring robust computing platform capacity, provide a more thorough analysis of the growth, development, and movement of the fire, as well as its associated products of combustion.

Probabilistic data and tools are essentially used to gauge the occurrence of a given event or a given result once a challenge is applied to a building or structure. Expected value risk models are included in this category and can be used to establish likely outcomes of a given event or scenario. In other words, how likely is it that a given hazard scenario may occur in a given building, and what is the consequence should that hazard scenario occur.

Heuristic methods allow the true creativity (with limits) of the design community to be put fourth. In the US, this has allowed code development organizations to look well beyond our borders and to more formally see how fire protection approaches differ in other countries. In a much broader sense, this area has also brought together various international entities to evaluate key issues that surround the use of PB design options. Notable work includes that of the International Council for Research and Innovation in Building and Construction (CIB, 1998). One method under discussion by CIB involves a whole building approach. In this method, five broad, building categories are identified. Corresponding building attributes are then identified and segmented into three categories. This building performance matrix can then be used to inter-relate the categories and the attributes. Whole building parts are included in Table 2. The related building attributes are in Table 3.

Arguably, it can be defended either way that all of the subcategories impact or relate to the fire protection needs of a building. In the specific case of tall buildings, PB designs must consider the functional needs of the client – which is likely to translate to the number of building occupants. This value alone will begin to drive useable square meters on a given floor. Space taken up by elevator shafts, exit stairs and HVAC and utility shafts must all be considered in the PB design analysis. In these examples, building component parts which improve access (mechanical transport), and which can be used in a time of emergency (exit stairs), must also be evaluated as smoke transport conduits.

Smoke movement in tall buildings is a sometimes-contentious subject. Should vertical smoke movement in a tall building be completely non-existent, or is it reasonable to expect, and even tolerate some 'acceptable' amount of smoke on upper floors provided it does not contain lethal by-products? Current prescriptive code rules in the US provide numerous requirements for enclosing vertical shafts in multiple story buildings, yet these rules do not specify a pass/fail rule for smoke movement in the field. Overall PB design strategies will be able to help quantify such subjective criteria.

Table 2 Whole building parts.

CATEGORY	SUBCATEGORY	RELATED TO FIRE PROTECTION
SPACE	Functional Space	ü
	Building Envelope Space	
STRUCTURE	Sub-structure	
	Super-structure	ü
EXTERNAL ENCLOSURE	Below ground	ü
	Above ground	ü
INTERNAL ENCLOSURE	Vertical	ü
	Horizontal	ü
	Inclined	ü
SERVICES	Plumbing (Water and waste)	
	Heating, Ventilation and Air Conditioning	ü
	Fuel System	
	Electrical system	ü
	Communication system	ü
	Mechanical transport	
	Security and protection	ü
	Fitting	ü

Installation of select, specific systems such as automatic sprinkler systems will all but be insured in the tall building environment. While continuing to be a standing, prescribed system in many codes for the tall building environment, it is nearly inconceivable that a thorough PB design will include an acceptable solution that does not include the installation of an automatic sprinkler system. Nonetheless, PB design recognition will at least open the possibility that someone will at least consider such an option.

As previously stated, PB design is going to be reserved for all but the most challenging and exigent projects. Tomorrow's tall building designers will have more design options available, but issues of reliability, redundancy, predictability, safety factors and conservatism are still being actively debated in the fire protection engineering community.

Table 3 Related building attributes.

CATEGORY	SUBCATEGORY	RELATED TO FIRE PROTECTION
SAFETY	Structural	ü
	Fire	ü
	Accident (Safety in Use)	
HABITABILITY	Structural Serviceability	
	Thermal Comfort	
	Tightness (Water and Air)	
	Air Quality	
	Acoustic	
	Lighting	ü
	Access	ü
	Security	ü
	Condensation	
	Health and Hygiene	ü
	Functionality	
	Adaptability	
	Aesthetic	
SUSTAINABILITY	Maintainability	ü
	Durability	ü
	Economics	ü
	Decommission	
	Environmental Friendliness	ü

A generally agreed upon approach to help leverage PB design options into the larger picture of tall building design should set or consider six goals. These goals include:

1. Life Safety of Building Occupants
2. Property/Contents Protection
3. Mission Continuity
4. Environmental Consequence of Fire
5. Heritage/Cultural Preservation
6. Fire Suppression Personnel Safety

These elements can begin to set the stage for PB design. The CTBUH as an organization is an obvious venue to share PB design ideas in fields as diverse as steel erection techniques, concrete batching methods and challenges associated with adding larger populations to the tall building environment. PB fire protection engineering design, which is the newest entry into the field of PB design, can contribute to overall goals of allowing larger buildings to continue to be safely built. Innovative and novel design techniques can be safely used to establish reasonable goals and objectives to keep occupants of the tall building environment safe, and to ensure that fire suppression personnel are properly trained, protected and able to safely take any necessary actions to control and supplement automatic fire suppression systems. The end results of a more general movement towards PB design in the fire protection engineering community should contribute to safer buildings, more economical design, and use of improved materials and methods. The added return is also likely to provide improvements to the established status quo of prescriptive code regulations.

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