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Application of Performance-Based Fire Safety Design
性能化防火设计的应用

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It is well known that fire problems in super high-rise buildings are common issues throughout the world. Fire technology covers fire prevention, fire suppression, and fire safety engineering. The application of science and engineering principles can protect skyscraper occupants from destructive fire. This chapter addresses some of the features of the Shanghai Tower and the fire safety challenges faced by the Tower. It then describes the application of a performance-based approach and modern fire technologies in the tower.

众所周知，超高层建筑的消防安全问题是世界性的难题。消防技术涵盖火灾预防、火灾扑救以及消防安全工程。应用科学及工程原理能够保障人员的生命安全并避免火灾对超高层建筑的破坏。 本文将重点阐述上海中心大厦的一些重要特征及大厦所面临的消防安全方面的挑战。之后，还将说明性能化消防设计及现代消防技术在大厦中的应用。

Fire Safety Challenges Faced by Shanghai Tower

Structure Safety Challenge

Structural safety is paramount to building safety and also the basis of design for structural fire protection. The fire resistance rating of the main structures, such as the core with steel reinforced concrete shear walls, steel reinforced concrete columns, steel trusses, beams, and curtain wall supporting system each contribute directly to the fire safety of the tower (see Figure 4.5).

Safety Evacuation Challenge

It is proven through modeling and case studies that evacuation time is directly proportional to building height and the occupant density of the building. The higher the building, the more people it accommodates, which require more time for evacuation. Based on simulations and quantitative analyses, the tower could reach an occupant load of 31,300 people. It will be very challenging to evacuate this number of occupants in case of a fire.

Atrium Fire Safety Challenge

The innovative and sustainable design of the tower incorporates two separate curtain walls, the exterior one is spiral-shaped, and the interior one is cylindrical. The space between the curtain walls varies from 1.0m at the narrowest point to more than 10m at the widest, forming 12-15-story tall open space atria, which will house the landscaped sky gardens at each zone throughout the building. The landscaped sky lobbies will be the social and retail hubs for each zone. The fire resistance rating of the interior curtain wall, smoke control, fire detection, and fire suppression system in the atria creates fire safety not only for the atria but also for the whole tower.

Reliable Water Supply Challenge

It is practically impossible to ensure fire safety for the building without a reliable water supply, because it is fundamental to water-based fire extinguishing system. How to transfer fire water to the floors above 600m and how to reliably transport water to the top of the building directly affects the fire safety of the tower and poses challenges to the design team.

上海中心大厦面临的消防安全挑战

结构消防安全问题

建筑结构的安全是整个建筑的生命线，也是建筑防火设计的基础。上海中心大厦采用的钢筋混泥土剪力墙核心筒，钢筋钢板混泥土巨柱，钢结构伸臂桁架和钢结构幕墙支撑体系，其耐火极限直接关系到整个建筑的消防安全 (见图4.5) 。

人员安全疏散问题

根据计算机模拟和实际案例研究，建筑内的人员疏散时间与建筑高度和人员密度成正比。建筑越高、人数越多，所需疏散时间越长。根据使用功能和建筑规模计算，上海中心大厦可容纳3.13万多人。火灾时保障人员安全疏散是一个非常棘手的问题。

中庭消防安全问题

作为设计创新和绿色建筑，上海中心大厦采用内外双层玻璃幕墙，内外幕墙之间最窄处仅1.0m左右，最宽处有10m多，每区内外幕墙之间形成12层~15层高的开放式的园景中庭，将成为大楼各区的社交与配套服务中心。中庭内幕墙的耐火极限、中庭的防烟排烟以及火灾探测、灭火设施配置既关系到中庭的消防安全，也关系到大厦的整体消防安全。

Figure 4.4. Exterior podium of the Shanghai Tower (Source: Gensler)
图4.4. 上海中心大厦外部裙房 (来源: Gensler)

Application of Performance-Based Fire Safety Design in Shanghai Tower

For many buildings that are straightforward in size, shape, and use, prescriptive codes provide the designer with sufficient guidance. The prescriptive codes, in which goals and objectives are absent, set forth minimum requirements for protection and are generic by occupancy. Examples include spacing requirements for fire compartments, detectors, sprinklers, fire resistance ratings, and maximum travel distances. It is relatively convenient for designers and reviewers to adopt the prescriptive codes.

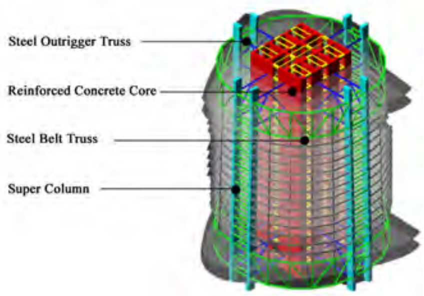

Figure 4.5. Tower Structure (Source: Gensler, 2009)
图4.5. 大厦结构 (来源: Gensler, 2009)

消防供水可靠性问题

如果没有可靠的供水系统，就不能保证大楼的安全，因为消防给水的可靠性，是建筑消防水灭火系统的根本，也是建筑消防安全的保障。如何把水供给到600m高的楼层，并保持大楼顶部消防供水的可靠性，直接关系到上海中心大厦的消防安全，也是设计团队面临的挑战。

上海中心大厦性能化防火设计的应用

对于大小尺寸、建筑形状、使用功能简单的建筑来说，处方式规范可为建筑设计人员提供足够的指导。处方式规范的目的和目标明确，设定了消防的基本要求，例如，对防火分区面积、火灾探测器设置、洒水喷淋头布置、建筑耐火等级、最大疏散距离等，都有明确的规定要求。所以，采用处方式规范对设计人员和审核人员来说，是相对比较方便的。

但是，火灾探测、火灾扑救、烟雾控制的处方式要求也许不适应设计场所热梯度和气流形状，其结果是造成火灾探测器和洒水喷头动作响应的延误，或不能有效控制烟气。所以处方式设计有时不能满足建筑业主、设计人员和官方审核人员的需求和期望，特别是对于商业中心和中庭等复杂的高大空间建筑来说，更是如此。

近年来，性能化防火设计的理念日益被人们所接受采纳，以弥补处方式设计的不足。一般而言，性能化防火设计主要解决高大共享空间的防火分区、安全疏散、烟气控制、结构保护、消防设施配置等方面的消防安全难题。针对上海中心大厦的建筑特点和面临的消防安全难题，性能化防火设计主要解决中庭消防安全和安全疏散的疑难问题。

中庭建筑结构消防保护措施

利用计算流体力学软件FDS模拟，设计2个8MW快速时间平方火灾场景模拟，主要分析评估中庭的火灾温度。1个火灾场景位于内外幕墙之间的距离为2m处，另1个火灾场景位于内外幕墙之间的距离为4m处，火灾场景效果参见图4.6和图4.7。FDS的输入参数见表4.2，模拟时间为20分钟。模拟结果显示，内外幕墙之间的距离为2m处，烟囱效应明显; 内外幕墙之间的距离为4m处，烟囱效应减弱，模拟结果见表4.3。根据FDS模拟结果和性能化分析，吊杆及对应高度范围内的水平支撑构件、顶层环梁应采用防火保护措施，使钢

However, prescriptive detection, suppression and smoke control requirements may not adequately account for the range of thermal gradients and air flow patterns within the design space. It may result in delayed detection or suppression response, or failure to control smoke movement. Also, the prescriptive approach may not always meet the needs or expectations of building owners, designers, or official reviewers, especially for more complex buildings, high-ceiling or large-volume spaces, such as shopping malls, atriums etc.

In recent years, the concept of performance based fire safety design has been favorably received as a means to address some of the disadvantages in prescriptive approaches. Generally speaking, performance-based approaches usually solve fire safety problems involving fire compartment isolation, safety evacuation, smoke control, structure fire protection, and fire facility configuration in large-scaled space. Based on characteristics and the functions of Shanghai Tower, a performance-based approach was mainly applied to solve the problems of atrium fire protection and safety evacuation where the current prescriptive Chinese fire codes cannot be followed.

Fire Protection for Atrium Building Structure

Applying the computational fluid dynamics software of Fire Dynamic Simulator (hereinafter referred to as FDS), the analysis specifically evaluated the ambient temperature of fire in the atrium from 2 design fires. Two fire scenario models are shown in Figure 4.6 and Figure 4.7. Detailed FDS input parameters are shown in Table 4.2, where a duration of 20 minutes was modeled. It was found from FDS modeling that a chimney effect is obvious in the atrium, where there is 2m distance between the curtain walls, but the effect is reduced where the space between curtains reaches 4m, as shown in Table 4.3. According to the FDS results, steel structure components that include belt trusses; horizontal bracings and radial supports; and the top belt trusses of the atrium, should be protected by fireproof coating in order to increase the steel structure's fire resistance rating to nothing less than 1.5 hours (see Table 4.2 and Table 4.3).

Two types of curtain walls are used for the interior wall, namely B1 and B8. The B1 wall, which is an aluminum unitized curtain wall with laminated tempered glass and fire resistant glass, is installed in locations where the environment temperatures do not reach 240 °C (in case of fire), from level 4 to the top of each atrium, and in areas protected by a window sprinkler system. The B8 curtain, which is an aluminum unitized glass curtain wall with hollow fire resistance glass, is installed in locations where the temperature exceeds 240 °C on the bottom 3 floors of the atrium. Theses designs were proven correct and reasonable by the results of fire tests conducted by Tianjing Fire Research Institute.

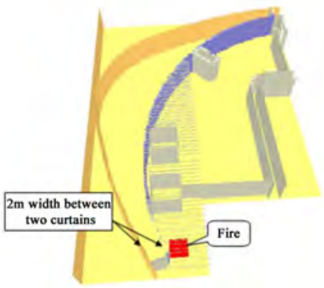

Figure 4.6. Fire Scenario – Model A (Source: Gensler, 2009)
图4.6. 火灾场景一模型A (来源: Gensler, 2009)

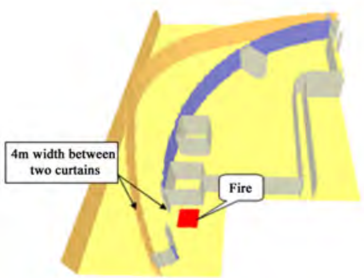

Figure 4.7. Fire Scenario – Model B (Source: Gensler, 2009)
图4.7. 火灾场景一模型B (来源: Gensler, 2009)

结构构件的耐火极限不低于1.5h (见表4.2及表4.3) 。

对建筑玻璃内幕墙，采用B1幕墙和B8幕墙两种方式。其中，B1幕墙采用铝框单元式玻璃幕墙，玻璃为中空夹胶玻璃 (中庭侧) +C类防火玻璃 (室内侧) ，设于火灾环境下最高温度不大于摄氏240度的区域，即每个中庭第4层至中庭顶部区域，并设置窗喷淋保护措施; B8幕墙采用钢框单元式玻璃幕墙，中空玻璃内外侧均为C类防火玻璃，设于火灾环境下最高温度可能大于摄氏240度的区域，即中庭底部的3个层面。天津消防研究所进行的火灾试验结果证明，这样的设计是安全和合理的。

中庭消防设施的配置

性能化防火设计综合考虑消防策略，将各个消防系统有机整合起来，而不是将其隔离开来或机械的叠加。如何有效地配置中庭的火灾报警系统和灭火系统，是一个重要的课题。根据计算机模拟和性能化分析，9个区段的每个大空间中庭分三层设置空气采样火灾自动报警系统，其火灾探测点设置在中庭底部距楼板10m高的灯架处、中庭中部和中庭顶部，并在中庭10m处设置自动跟踪扫描智能射水灭火系统，以提高中庭火灾报警和自动灭火的有效性和可靠性。

烟气蔓延和排烟效果与中庭的气流分布、建筑形状和火灾部位密切相关。因此在确定中庭的控烟方式前，运用计算流体力学软件，对中庭的烟气流动和烟气控制进行计算机模拟。根据FDS模拟结果和适用的火灾场景，中庭排烟量取值为220,000m^3/h，采取上排下送的模式，即在每个中庭的顶部利用设备层设置机械排烟风机进行排烟，中庭的底部进行机械补风。

垂直安全疏散的设计

对于上海中心大厦来说，由于建筑超高，人员众多，确保人员安全疏散尤为关键。上海中心大厦的疏散设计，在三维仿真疏散软件STEPS计算机模拟和FDS模拟火灾场景的基础上，应用性能化方法，进行优化完善。

首先，根据建筑面积和人员数量设计安全疏散楼梯。1区包括裙房，体量大，人员多，所以在2层设计19座楼梯，3、4层设计17座楼梯，5层设计16座楼梯，6层设计7座

Fire scale 火灾规模	8MW兆瓦
Fire type 火灾类型	t-square fast fire T型快速火焰
Fire source area 火源面积	3.3x3.3=10.9m² 平方米
Heat release rate 释热率	550kW/m² 千瓦/平方米
smoke generation rate 烟生成率	0.05
Fire A position 火灾模型A位置	2m distance between two curtains 内外幕墙之间的距离为2m
Fire B position 火灾模型B位置	4m distance between two curtains 内外幕墙之间的距离为4m
Fire grid size 火网尺寸	0.1m (米) x0.1m (米) x0.1m (米)
Outdoor temperature 室外温度	40℃
Indoor temperature 室内温度	24℃
smoke extraction volume 排烟体积	220000m³/h立方米/小时
make-up volume 补风体积	110000m³/h立方米/小时

Table 4.2. FDS input parameters
表4.2. 模型输入参数

Height 高度 Scenario 场景	Temperature 温度 (℃)		
	5m（米）	10m（米）	55m（米）
Fire A 火型A	500	250	240
Fire B 火型B	500	200	180

Table 4.3. FDS modeling results
表4.3. FDS模拟结果

Fire Facilities Designed for the Atrium

Performance based design results in a comprehensive fire protection strategy in which all fire protection systems are integrated rather than isolated. Equipping the atrium with an efficient fire alarm and fire extinguishing system is a key issue. In response to simulation results, every atrium is designed with three layers of air sampling detection systems, for the purpose of improving the availability and reliability of fire detection and alarming systems. The detectors are located at the bottom, in the light rail 10m from the atrium floor, and at the middle and top of the atrium. An automatic water fire extinguishing system is also provided 10m above the lobby floor, in order to increase the level of fire protection for the tower.

The effects of smoke spread and smoke exhaust is closely related with air distribution, building shape, and the location of the fire in the atrium. Therefore, using the CFD, a simulation for smoke movement and smoke control was conducted for the atrium before the smoke control method was selected. Based on the CFD results and suitable fire scenarios, the capacity of smoke extraction in the atrium was recommended to be 220,000m³/h. Additionally, it was found that the ideal location for ventilation systems are at the top of the atria, while the make-up air supply should be located at the bottom of each atrium in the tower.

楼梯，7层设计4座楼梯。2区至4区设置4座防烟楼梯间。根据楼层面积的缩小，楼梯数量也相应减少。5区和6区设置3座防烟楼梯间，7区至9区设置2座防烟楼梯间。楼梯布置参见图4.8、图4.9和图4.10。此外，在7、21、36、51、67、83、100、116层设置了避难层 (区)，空中休闲大堂的每个中庭中均设有1个通往下层避难层 (区) 的疏散楼梯。

其次，应用高速穿梭电梯作为辅助安全疏散设施。根据性能化设计分析技术，采用STEPS模拟，如果利用疏散楼梯将楼内人员疏散完毕，需要138分钟。为了提高上海中心大厦人员的疏散效率，对13台高速穿梭电梯采取防火、防烟、防水的电梯井和保障供电等技术措施，用于火灾等紧急情况下辅助人员疏散，火灾时穿梭电梯停靠避难层，将避难层的人员疏散至地面，提高大厦整体人员疏散的效能，时间缩短为108分钟。

再次，上海中心大厦设置了先进的集中控制智能型消防应急照明和疏散指示系统。该系统与FAS系统联动，可以根据FAS的火灾信息，选择相应的疏散预案，适时调整疏散指示方向，提高建筑内人员安全疏散的效率。传统的疏散指示标志灯具都以独立单体的形式出现，而且都是静态的，无法根据火灾情况调整疏散指示方向,因而往往会影响火灾时疏散诱导的安全性。

大厦消防供水设计

上海中心大厦室内的消防给水采用重力供水和临时高压供水相结合的方式，116层以上采取临时高压消防给水系统，B5至115层采取重力给水系统，在B5、20、50、83、116分别设置消防水池水箱和消防传输泵接力供水，在128层屋顶设置屋顶消防水箱，除了接力转输水管外，作为冗余措施，另设置200mm的水管将6个水箱串连起来。此外，设置2根从B5直通顶层的DN100压缩空气泡沫灭火专用立管，在地面设置水泵接合器，在每个楼层设置栓口，为消防灭火救援提供了更为有利的条件。

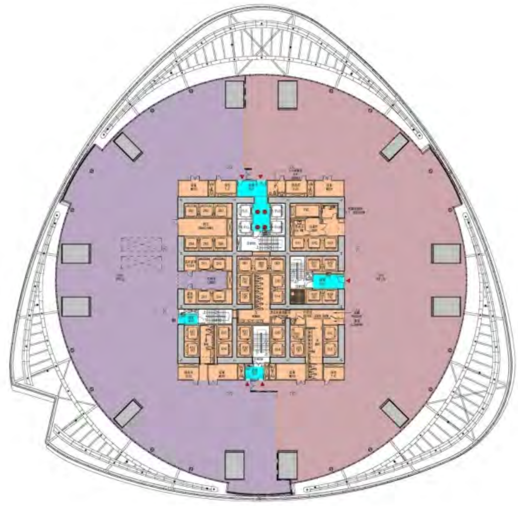

Figure 4.8. Arrangement of Stairs in Zone 2 (Source: Gensler, 2009)
图4.8. 区域2内楼梯布局 (来源: Gensler, 2009)

Vertical Evacuation Methods Designed for the Building

Safety evacuation is a hot topic for Shanghai Tower, because of its height and its large number of occupants. The safety evacuation design was improved and perfected for the tower using a performance-based approach that relied on results from the design of fire scenarios from the FDS and from computer simulations of evacuation using the Simulation of Transient Evacuation and Pedestrian Movements (hereinafter referred to as STEPS) software.

First, adequate egress stairs are designed for the tower according to the floor space and amount of occupants. Due to large floor space within the podium in zone 1, there are 19 stairs designed for level 2, 17 stairs for level 3 and level 4, 16 stairs for level 5, 7 stairs for level 6, and 4 stairs for level 7. For zone 2 to zone 4, 4 egress stairs are provided. Based on floor area, egress stairs are reduced to 3 in zone 5 and 6, and 2 in zone 7 to zone 9. In addition to the stairs provided above, there is also one additional egress stair for each atrium sky lobby to the refuge areas located on level 7, 21, 36, 51, 67, 83,100 and 116 in the building (see Figures 4.8–4.10).

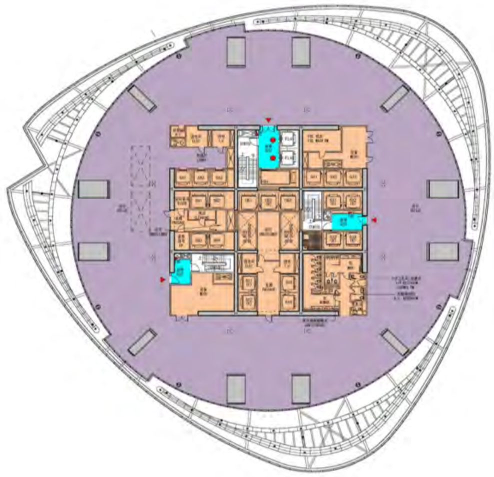

Figure 4.9. Arrangement of Stairs in Zone 5 (Source: Gensler, 2009)
图4.9. 区域5内楼梯布局 (来源: Gensler, 2009)

Second, shuttle elevators are designed for supplemental safety evacuation. Based on the case study and simulations by STEPS, the conclusion shows that it will take about 138 minutes to evacuate every occupant from the building by stairs. In order to improve the efficiency of evacuation, 13 high-speed shuttle elevators are allocated for use during emergency evacuations. These elevators, which are designed to be fire-proof, water-proof, and have smoke-proof shafts and a dependable power supply, will be driven to the respective refuge floors to take people to the ground level in case of a fire, or emergency evacuation, reducing the evacuation time to 108 minutes.

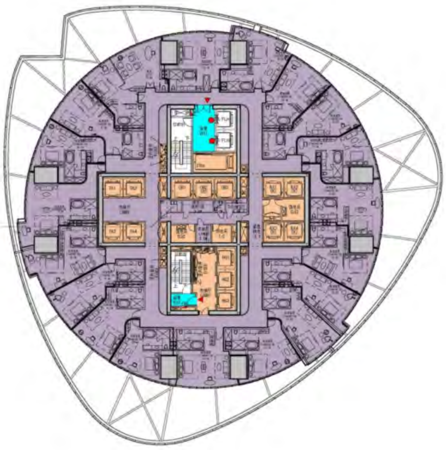

Figure 4.10. Arrangement of Stairs in Zone 7 (Source: Gensler, 2009)
图4.10. 区域7内楼梯布局 (来源: Gensler, 2009)

Third, in order to improve evacuation efficiency, Shanghai Tower is designed with a centrally controlled intelligent fire emergency lighting system which is coordinated with the fire alarm system and automatically changes the direction of evacuation signs based on fire information from the fire alarm system. Traditional fire emergency lighting and evacuation indication systems do not allow the evacuation direction to change with the situation in an event of a fire as they are single point units, and as a result may affect safe evacuations.

Gravity Water Supply System Applied in the Building
A combination of a gravity-fed water supply and temporary high-pressure water supply is provided in Shanghai Tower. The gravity-fed water supply is used for level B5 to level 115 and the temporary high-pressure water supply is used from level 116 to the top of the tower. The gravity-fed water tanks and transfer pumps are located on basement 5, level 20, 50, 83, and 116. There is also one roof water tank on level 128. These 6 water tanks are further connected in series by a 200mm water pipe, adjacent to the transfer pipes, as redundancy will improve the reliability of the water supply. Additionally, two independent stainless pipes are provided between the fire department connection on the ground and fire hydrant outlets on every floor to supply compressed air foam from fire trucks, for the convenience of the fire fighting operation.

Conclusion

Fire safety of super high-rise buildings is a very complicated systematic engineering problem covering fire prevention and fire suppression. A performance-based design should be used to solve unusual and unique problems in large-scale projects where fire requirements are not fully addressed by codes or where strict compliance with codes compromises the function of the building for the purpose of ensuring the safety of occupants and the building itself.

结束语

超高层建筑消防安全，是一个极为复杂的系统工程。对于体量高大、功能复杂、设计新颖、人员密集的超高层建筑，当执行现行国家消防技术标准规范确实难以实现其功能和设计特色的，应采用性能化防火设计方法，解决消防疑难问题，保障建筑的消防安全水准。

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