Title: **Fifty Years of Fire Safety In Supertall Buildings**

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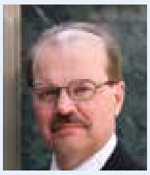

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Peter A. Weismantle, Director of Supertall Building Technology at AS+GG and formerly an Associate Partner at SOM Chicago, has been responsible for the technical design and coordination of systems including vertical transportation, fire and life safety and the building façade on projects including Broadgate, Ludgate, and Canary Wharf Developments in London; Jin Mao Tower, Shanghai; and the world's tallest building, Burj Khalifa in Dubai. Projects currently under construction include the Jeddah Tower (formerly Kingdom Tower), in Jeddah, Saudi Arabia, which, when completed, will be the first building in the world to be more than 1,000 meters.

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James Antell AIA, PE, has over 35 years of fire engineering experience, acting as an advisor to design teams and building owners on compliance with local and international fire safety codes. His experience includes development of fire protection design strategies using both code- and performance-based approaches. Mr. Antell's specific areas of concentration include high-rise buildings, public assembly facilities and healthcare. Mr. Antell's global high-rise fire engineering experience includes many of the world's tallest structures including projects in the United States, Asia, and the Middle East. He has presented worldwide on high-rise fire safety and published numerous articles on the subject.

Abstract

As international design teams participated in the development of high-rise structures around the world, many of the concepts of fire-safe design first introduced in the United States have been adopted, amended and otherwise modified to become global design standards. This process has been a joint effort of the architects and the fire engineers involved in supertall building design. Early adoption of and reliance on active fire suppression systems and the application of performance-based design, expert panels, peer review and special studies to validate building performance have evolved into standard practices worldwide. Although regional codes vary significantly, the overall fire-safety strategies, and the use of performance-based design tools to demonstrate compliance is used commonly on projects world-wide.

Keywords: Fire Safety, Mixed-Use, Performance-Based Design, Supertall

1969 and the Dawn of the New Era of the Tall Building

In 1969, there were only three buildings in the world that qualified as supertalls (i.e., buildings over 300 meters in height). Two in New York, the Empire State and Chrysler, and one in Chicago, the John Hancock, now 875 N. Michigan Avenue. The completion of the John Hancock occurred almost 40 years after the completion of the two supertalls in New York and signaled the start of a building boom that has, with a few notable periods of slowdown, continue to this day. Due to a booming economy in the United States in 1969, there were at least four supertalls on the drawing boards or under construction, as well a greater number of very-tall if not supertall buildings. Even today, in places like Chicago, the building boom of the late '60s and early '70s still forms a great part of the public's image of the city.

The unique issues and technical challenges posed by tall buildings were recognized by the professionals of that time who were involved in the design of these buildings and resulted in the founding of organizations such as the Chicago Committee on High-Rise Buildings (CCHRB) and Council on Tall Buildings and Urban Habitat, shortly thereafter. Those organizations initially focused on the structural aspects of building tall, but their fields of interest quickly expanded to the unique aspects of fire safety. Fundamental concepts of fire safety that gained particular attention included:

- Control of fire
- Occupant evacuation
- Firefighting features
- Limiting smoke spread

Building Codes enforced at the time however, did not include provisions specifically for high-rise buildings. Therefore, those special issues critical to safety in very tall buildings were generally not addressed and any building, whether six stories or 60, could be designed and constructed to the same standard. In the case of Chicago, the 1969 edition of the Chicago Building Code was little changed from that as published in 1949 and in New York, they were in the midst of updating their 1938 code edition. But of course; design, technology, logistics and economics of construction had been racing ahead.

As a result of this situation, preceding updates to the codes, the design of the tall buildings of this era proceeded based on "Best Practices". Specific areas addressed by some, if not all projects included:

- Fire rated structural frame
- Fire rated stair enclosures and shafts
- Fire department standpipes and water supply
- Firefighter service for elevators
- Firefighter communication system
- Fire command center
- Some buildings were protected with fire sprinklers however, most were not.

875 North Michigan Avenue (formerly John Hancock Center), Chicago

The supertall 875 North Michigan Avenue represents a typical example of the fire protection strategies used in the 1960s and 1970s. The building is one of the earliest examples of a mixed-use high-rise incorporating retail at the base, office, hotel and condominium uses. Furthermore, this building is the first supertall high-rise built in Chicago.

The fire protection approach to the project includes elements that are still basic features of high-rise structures to this day. The strategy of defending occupants in-place from fire and its effects developed on 875 North Michigan Avenue became the basis for the high-rise building requirements of the Chicago Building Code and later was incorporated into the model building codes in the United States. This strategy incorporates a number of fundamental elements:

- Passive measures including structural fire resistance and fire compartments and barriers to limit fire and smoke spread allowing occupants to remain in place without full building evacuation.
- Enclosed exit stairs to facilitate occupant evacuation from the fire area to grade or to other safe areas within the building. In this case, exit stairs are designed as "smokeproof towers" utilizing a naturally ventilated vestibule designed to vent smoke entering from the fire floor and keeping it from entering the protected exit stair.
- A fire detection and alarm system to detect the fire location (by floor) and alert the fire department to respond. As is still the case in Chicago, occupant notification alarms are not automatic and are initiated by the fire department when deemed necessary.
- A firefighting standpipe system with adequate water supply in the form of water tanks and pumps to facilitate firefighting operations at any level inside the building.
- A fire department elevator provided with emergency power and controls and protected by a fire rated vestibule at each level to enable the responding fire department to reach the fire area quickly and safely.

Codes Catch-up in the 1970s

With the acceleration in tall building activity, there was a lot of pressure on the local authorities to establish up-to-date standards for the design and construction of this very particular building type. In the early 1970s, the fire protection strategies already being applied to high-rise design were codified into building regulations. This first occurred in major cities including Chicago and New York and later included the model building codes used throughout the United States. Of note is the fact that most of these first generation codes permitted both a sprinkler protection option and a non-sprinklered, compartmentalization option. Most first generation high rises were not sprinkler protected. It was only after several high-rise fires in the early 1980s that the codes mandated sprinkler protection in new construction and eventually in most existing high rises as well.

1990s and the Proliferation of Tall Buildings in Asia

With the first "Energy Crisis" of the mid-1970s, tall building construction slowed significantly in the United States. Briefly, tall building activity spiked in the Middle East, but few if any significant advances occurred in the design of those structures as related to fire and life safety. This lull in construction continued with the financial "crisis" and economic "slowdown" in the United States of the early to mid-1980s. However, by 1993, Deng Xiaoping's "Open Door Policy" had jump-started the Chinese economy to the point that major building projects, including clusters of very-tall and supertall buildings were being planned for the coastal cities of China. Other locations in Asia, such industrializing Taiwan and resource rich Malaysia, followed suit. This new wave of high-rise construction attracted design professionals with tall building experience from around the world and especially the United States.

Those international practitioners brought with them their experience in designing to the updated local US and model codes with their recognized high-rise provisions, but also encountered local Chinese practices embedded in the Chinese High-Rise Code of 1995. Furthermore, these parts of the world did not have the tradition, background, education or experience with very tall buildings and the sophisticated and complex systems that are inherent in their design. It was important that the architect and the full consultant team keep in mind "first principles" when designing the fire safety systems for these unique structures. "Passive" along with "Active," "Simple" along with "Sophisticated," "Local" along with "International," "Redundancy and Resiliency" and "Standards and Enhancements," were all concepts that needed to be applied on these early projects in the developing world.

Country	Location of Refuge Areas	Size of Refuge Areas	Ventilation
USA	Every floor of a high-rise building is considered a refuge area during fire. Floors are of two-hour fire rated construction with protection of penetrating shafts.	No provision is made for size of refuge areas. Because each floor is considered a refuge area, it is assumed that each floor can accommodate the occupant load from one other floor.	No requirement
China	Current Chinese Code limits vertical separation of refuge floors to 45 meters (between 10 and 14 floors depending on the floor to floor height).	Refuge areas can only share floors with mechanical equipment areas, although refuge area sharing floors with occupied areas is permitted under some situations. Refuge areas are required to hold the entire population of the floors that it serves at a density of 0.2 m^2 per occupant	Natural ventilation or mechanical pressurization
Korea	Refuge floors are required in high rise buildings. Refuge floors are to be located every 30 floors (they serve 29 floors). Refuge areas may be shared with mechanical equipment floors, but not with occupied floor levels.	By code, there is no guidance on refuge area size. By practice, refuge areas are to hold a percentage of the population served. At the highest levels, this is as high as 80%. On lower levels, it can be reduced to 40%	Natural ventilation or mechanical pressurization
Gulf Cooperation Council	GCC Code Circular requires full refuge floors every 20 floors (serving 19 floors). Refuge floors are required to be full floors with no other occupancy. They can be open to the exterior or mechanically pressurized.	The GCC Circular provides no guidance on occupant load. Refuge areas are required to be full floors and only HVAC equipment that serves only that floor may be located on it.	Natural ventilation or mechanical pressurization
India	The National Building Code of India requires refuge areas in high rise buildings located every 15 meters (4–5 floors depending on the floor to floor height) vertically.	Refuge areas sized for 0.3m^2/per person for occupants of two floors. Min. 15.0 m^2	Natural ventilation only
Jordan	Every three floors—two hour separation	Corridors are allowed to serve as refuge areas with two-hour separation from occupied areas.	Natural ventilation or mechanical pressurization
Singapore—For Residential Occupancies only	Refuge floors are required every 20 floors	Refuge floors are full building floors. They must accommodate 50% of the occupants of the floors they serve at a density of 0.3 m^2 per occupant.	Natural ventilation only

Table 1. Refuge Area Requirements—application of refuge floor requirements can take several forms based on local requirements and the form of the building.

Jin Mao and Petronas Towers Refuge Areas
As high-rise construction shifted to Asia, a number of new concepts were introduced that have become mainstream aspects of current high-rise fire safety. Two projects, Jin Mao Tower in Shanghai and the Petronas Towers in Kuala Lumpur, Malaysia represent some of the earliest applications of these concepts.

The concept of refuge floors or areas was first codified in Asia over 40 years ago. Since that time, they have been applied to high rise designs worldwide. The concept of refuge areas addresses a number of key challenges of high-rise evacuation including:

1. Most occupants of high-rise buildings are not physically able to evacuate from upper levels to grade without rest or assistance. Refuge areas provide a place within the building for occupants to wait protected from fire and its effects.

2. Refuge areas provide assembly points within the building to facilitate evacuation. Trained fire service or building personnel can use refuge areas to stage elevator evacuation, direct occupants to available stairs and facilitate an orderly evacuation process.

3. Refuge floors can act a fire breaks between floors. They contain no combustible materials so they will impede any vertical fire spread both internally and via the buildings' exterior curtain wall.

4. Refuge floors can be used to interrupt exit stair shafts. Stairs of more than 40 floors often create significant stack effect that can be difficult to overcome by mechanical pressurization. Limiting stair heights results in more manageable stack effect and reduces stack effect induced smoke spread.

Requirements for Refuge Areas vary significantly from country to country. Table 1 outlines requirements in a number of locations.

The Jin Mao Building incorporates refuge floors on the 15th and 30th floor of the office floors. In the hotel portion, refuge floors are used on all guest room floors. Refuge areas are partial floor areas shared with occupied office space. The exit stairs are interrupted, directing occupants into the areas of refuge at Levels 15 and 30, but are not interrupted Levels 58 and 85 (see Figures 1 and 2).

In Malaysia, refuge floors are not required by local code. Because of the unique design of the two Petronas towers with their connecting sky bridge on Levels 41 and 42 it was decided to use the sky bridges in combination with the associated sky lobbies in each tower as refuge areas that can be used to facilitate evacuation under a variety of scenarios (see Figure 3). It should be noted that Petronas was one of the earliest cases where elevators were considered for use on some emergency evacuation scenarios and where evacuation modeling was used to study the effects of elevators on full building evacuation times.

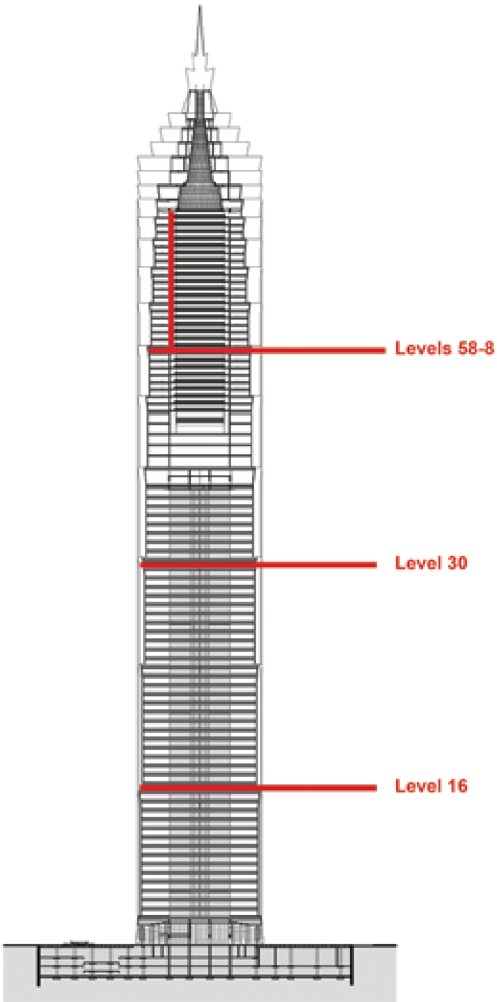

Figure 1. Jin Mao section—the exit stairs are interrupted, directing occupants into the areas of refuge at levels 15 and 30, but are not interrupted levels 58 and 85. © AS+GG

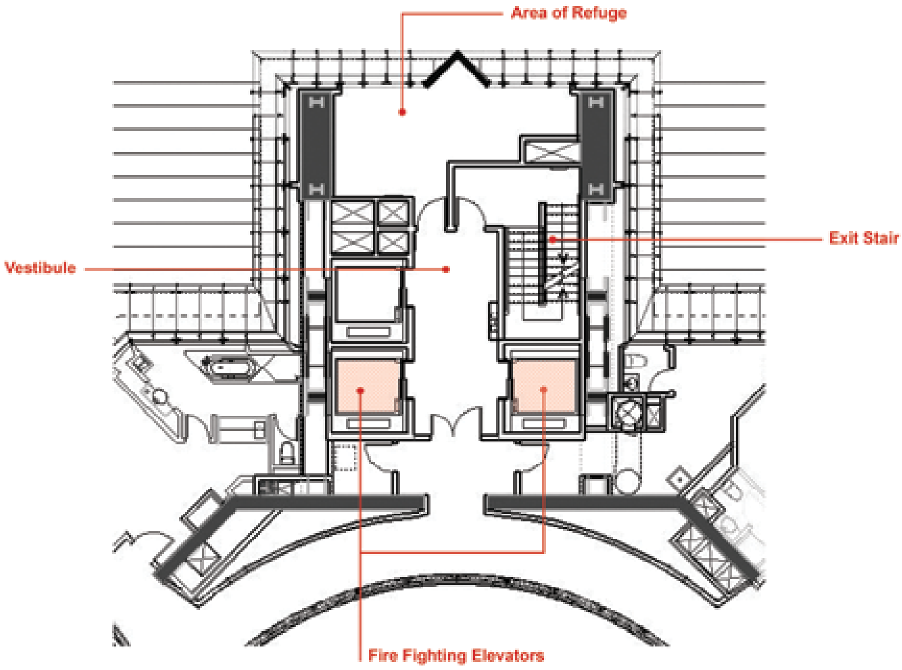

Figure 2. Jin Mao plan—refuge areas are partial floor areas shared with occupied office space. © AS+GG

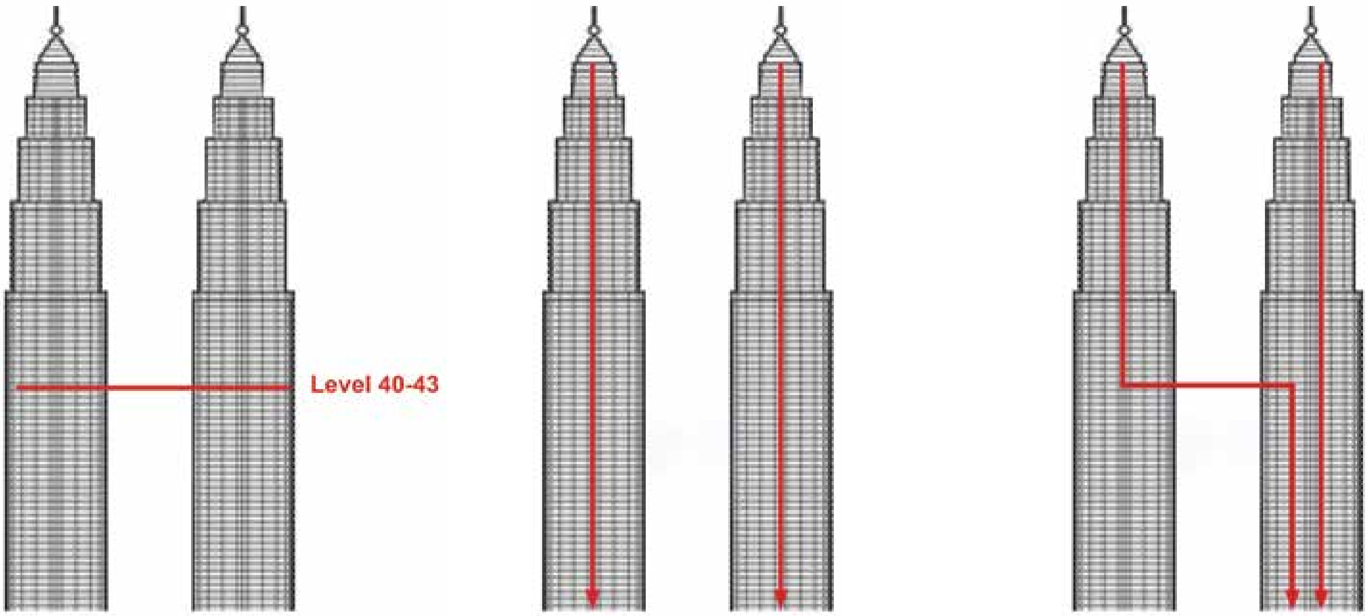

Figure 3. Petronas Tower Egress. © James Antell

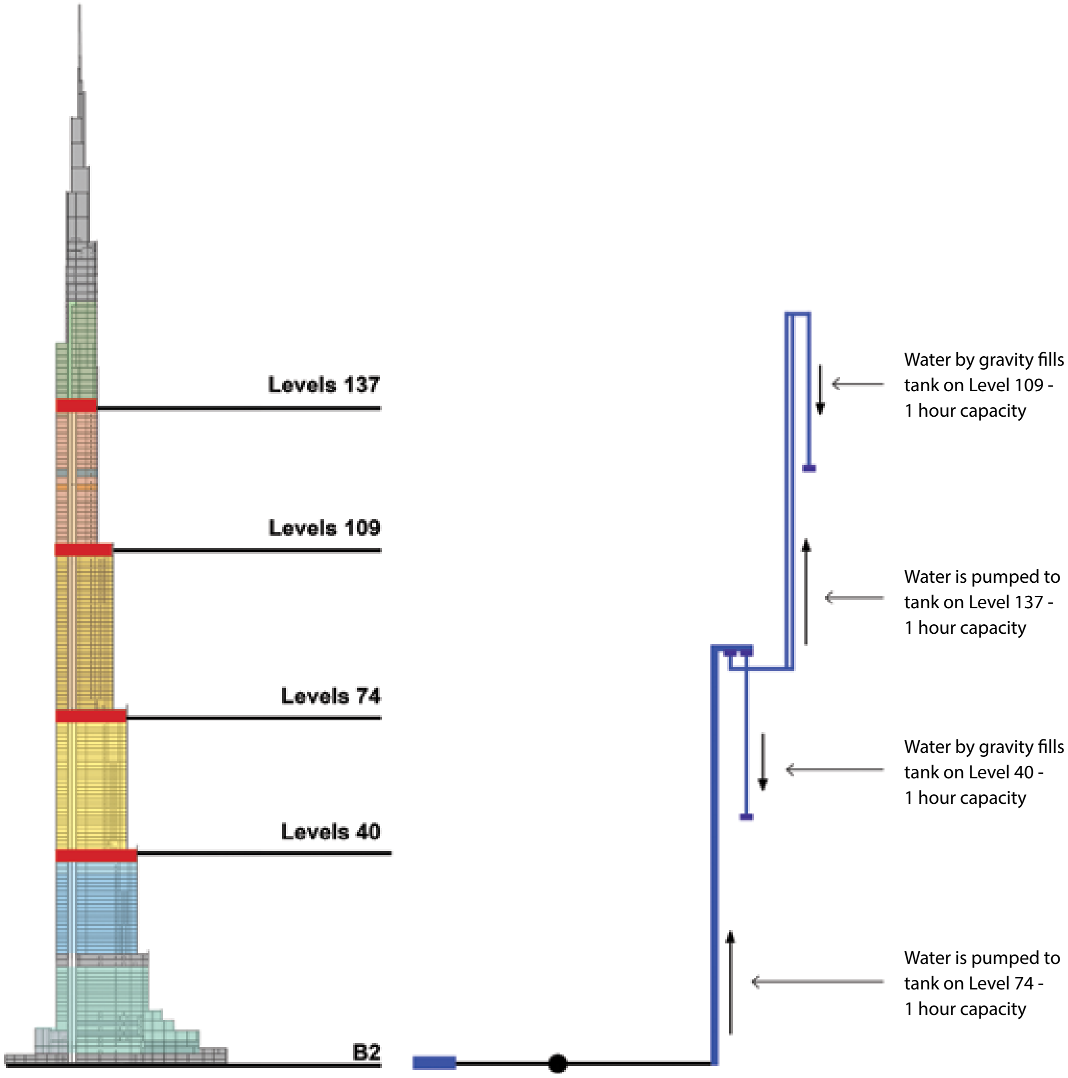

Figure 4. Internal water tanks for fire protection water supply are incorporated into the Burj Khalifa so that it is not reliant on municipal water for firefighting purposes. © AS+GG

Codes Catch-up in the 1990s

By the 1990s, the new International Codes, including updates of the those applied in China, had incorporated what were identified as the "Best Practices" of the earlier decades. The focus on the four Fundamentals Concepts of Fire Safety continued, but with enhancements due to the adoption of local practices and provisions as well as the introduction of forms of robustness and redundancy:

- Control of fire
  - o Universal adoption of sprinklers for high-rise buildings
  - o Self-sufficient firefighting water and emergency power
  - o Gravity based water supply for sprinklers and standpipe systems

- Occupant evacuation
  - o Refuge areas/safe areas
  - o Elevators for evacuation

- Firefighting features
  - o Exterior access requirements
  - o Fire-fighting elevator vestibules

- Limiting smoke spread
  - o Mechanical smoke control
  - o Firefighting elevator vestibules

Additionally, new and/or alternate approval processes were permitted. Those approaches include Performance Based Fire Safety Design and the requirement on certain high-profile projects for expert peer review panels.

2000s: 9/11 and Burj Khalifa

The Asian financial crisis of 1997 followed by the SARS epidemic of 2002 put a damper on tall building development in Asia for a period of time. Focus shifted to the Middle East. With the revenues from oil and the innovative financial approaches, countries like the UAE and began to compete in a tall building contest that, by the end of the decade, culminated with the opening of Burj Khalifa (2009).

Having stated the above, the events of 9/11 and responses by local authorities, design professionals, code developers and the public had and continue to have the most profound influence on tall building fire and life safety to this day. Specifically, the issue was no longer just fire alone, but issues related to systems robustness, redundancy, blast, intrusion, acts of nature and others potential scenarios needed to be addressed. These enhanced areas of concern produced changes in the design specifically reflected by:

- Robust structural systems
- Redundant water supply
- Full building evacuation including elevators
- Emergency response to broad range of emergency scenarios

Case Study: Burj Khalifa Fire Fighting Water Supply
The reliability of active fire suppression systems is a critical factor in high-rise fire safety. It is critical that these systems be simple and serviceable especially in developing countries. As a result, there is an increased emphasis on features that do not rely on municipal services such as water and electricity. The use of internal water tanks for fire protection water supply is incorporated into the Burj Khalifa so that it is not reliant on municipal water for firefighting purposes.

The sprinkler and standpipe systems operate by gravity so that a failure of the fire pumps will not impede the operation of these suppression systems. The Burj Khalifa uses a gravity fed fire protection water supply consisting of water tanks, piping and associated pumps for sprinkler systems and standpipe systems (see Figure 4).

Codes Catch-up in the 2000s

As a result of 9/11, the National Institute of Standards & Tests (NIST) made several recommendations to improve high-rise fire safety. These recommendations were incorporated into the 209 edition of the International Building Code (IBC) and are widely applied today. They include more rigorous requirements for building greater than 420 feet (128 meters) in height including:

- Higher fire resistance for the buildings structural frame and floor assemblies to enhance survivability from a prolonged fire event and allow occupant evacuation.
- Structural integrity of exit stairs and hoistways to resist impact loads and increase their usability during a fire.
- Multiple risers to supply water to sprinkler and standpipe systems in order to improve the reliability of these systems to fight fire.
- An additional exit stair so that of one stair is being used for firefighting operations, sufficient exits are still available for building occupants.
- Occupant Evacuation Elevators as an additional measure to facilitate full building evacuation in the event this becomes necessary.

2010s and the and the Proliferation of Tall Buildings in Asia and the Middle East

Case Study: Jeddah Tower Evacuation Elevators
There were many lessons learned from the tragedy of MGM Las Vegas Fire in 1980, where 85 people lost their lives. Arguably, following that event, the two most important changes reflected in the codes were the requirement for automatic sprinklers in high rise buildings and the recognition that the use of elevator systems during fire emergencies, as were then designed, should be discouraged. At that fire, three elevators became jammed in their hoistways. The use of heat sensitive call buttons was also prevalent, which resulted in the elevators answering a call from a fire floor, the door opening, even if passengers were occupying it, and death from asphyxiation due to smoke. However, since the World Trade Center tragedy of 9/11, there has been much discussion about speeding up the process of full building emergency evacuation. Specifically, the use of elevators to supplement the exit stairs, under certain circumstances, has been perceived as a no- or low-cost enhancement. As it stands now, both US model codes (IBC and NFPA) recognize the use of elevators, if properly designed and protected from fire and smoke, for supplemental building occupant evacuation.

In the case of Jeddah Tower, the local applicable codes do not recognize the use of elevators for means of escape. However, due to the great height of the building, the use of elevators to augment evacuation, primarily for "extraordinary" events, has been a fundamental aspect of the fire and life safety enhancements incorporated into the design. Partial or phased evacuation due to a "normal" emergency event, such as a fire in the building, would be handled in a normal manner via the exit stairs, without the use of elevators. However, in the case of "extraordinary" events, which could include, but are not necessarily limited to, district power outages, seismic events and general or specific security threats to the development, a tenant or to the building itself, would call into operation "Lifeboat" Evacuation (see Figure 5).

In the case of Jeddah Tower, designated elevators are designed to operate in a "Lifeboat Evacuation" mode that allows them to be used as an additional means of evacuation building occupants under certain emergency conditions. Lifeboat evacuation elevators are intended to be operated by trained building personnel. Once it is determined that it is safe to use this evacuation procedure, elevator controls allow trained personnel to operate designated elevators as part of an established evacuation procedure.

The high-speed shuttle elevators are used for lifeboat evacuation, shuttling occupants from designated refuge floors to the building lobby. The use of evacuation elevators for full building evacuation has been estimated using evacuation simulation quantitative modeling results in evacuation time of less than two hours. This time has been established in some locations as a benchmark criteria for full building evacuation.

Future Trends

As high-rise buildings continue to go higher and higher, new technologies and strategies will be required for fire safe design. New technologies will enhance occupant evacuation and firefighting by facilitating real time knowledge of emergent events. Occupants will be given dynamic evacuation instructions based on the location of the fire and on potential evacuation routes being used for firefighting operations. GPS and other web technologies will allow first responders to know the location of building occupants and facilitate egress. The Internet of Things (IoT) and Artificial Intelligence (AI) will be used to manage the decision making process in responding to emergencies.

The adoption of US model codes (primarily NFPA and ICC), with local amendments, is a recent trend in major cities In the United States such as New York and Chicago; as well as in other parts of the world such as Dubai and Saudi Arabia. The adoption of these codes, which not only contain prescriptive requirements but also performance-based options, reflect the fact the general acceptance of a uniform "international" approach to safety in tall buildings.

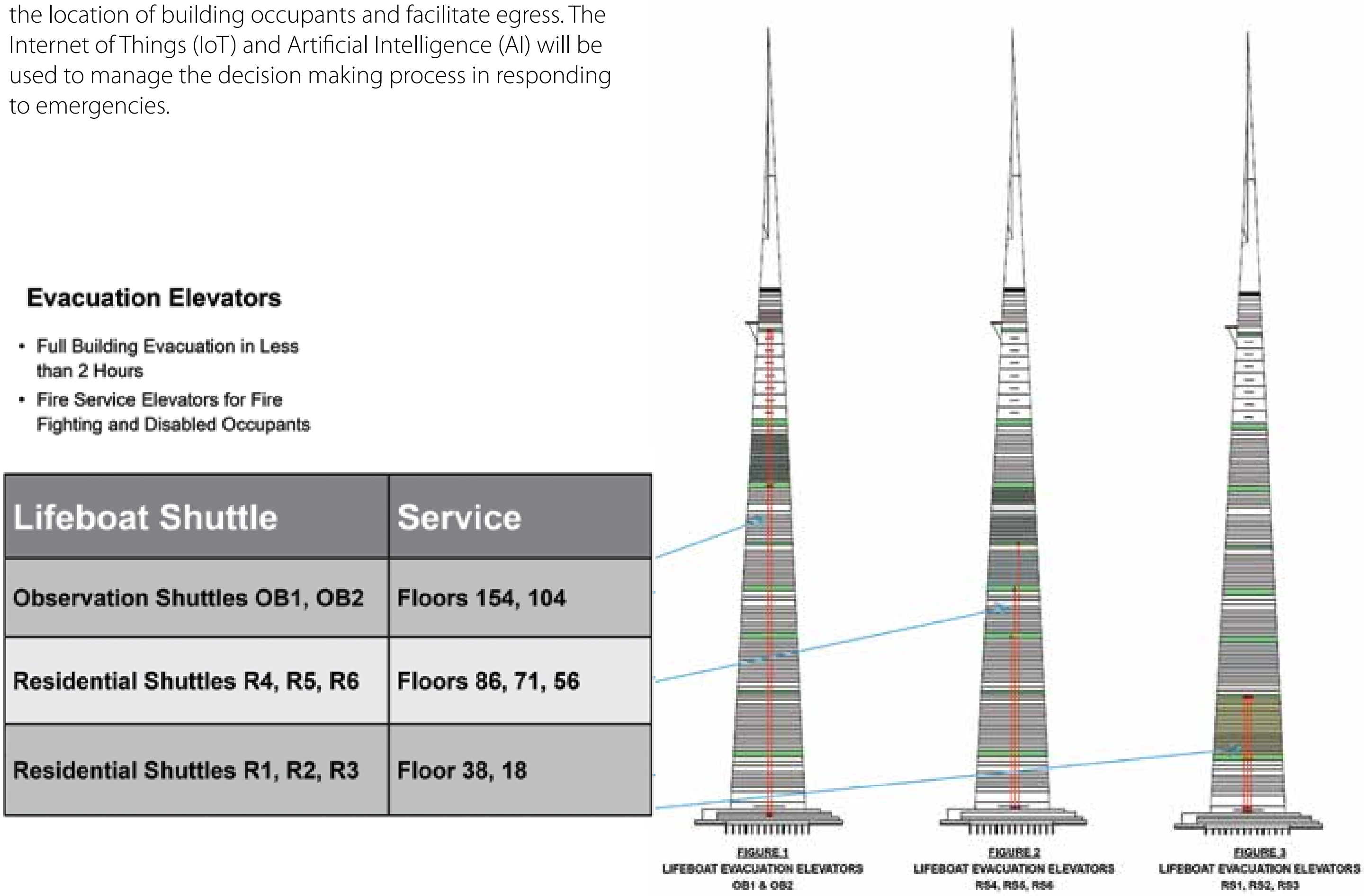

Figure 5. Jeddah Tower Evacuation Elevators are designed to operate in a "Lifeboat Evacuation" mode. © AS+GG