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Fire Safety and Prevention Issues in Design of Tall Buildings

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ABSTRACT

Fire safety design of tall buildings is crucial. The number of floors, the function, and the occupants' features build the complexity in the life and fire safety design of tall buildings. Because of the complexity of each tall building design, specific preventive measures are necessary more than the basic requirements given in the national and local codes. The fire safety design of the world-renowned tall buildings, including *Guangzhou International Finance Centre* (IFC), *Capital Market Authority (CMA) Tower, and Jin Mao Tower* are case studies and further focus is made on the facade design of tall buildings. The paper reviews the safety design issues and focuses on the fire evacuation models, estimations, and the effect of different parameters in the success of fire safety design of tall buildings. In addition to the various fire evacuation suggestions, the effect of human behavior in fire is also discussed through the literature review. Fire safety is not only an engineering problem to deal with, but also architects must know the holistic approach in the fire safety design of tall buildings since it involves their architectural design as well. The paper aimed to bring the most arguable issues in the fire safety design of tall buildings together and to highlight the value of different perspectives in achieving a promising fire safety design.

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1. Introduction

Tall buildings have become popular for several reasons. Urban areas still draw thousands every day and this increases the urban population, which requires more residential and office spaces. Urban lands are, therefore, in high demand and the prices climb higher as the demands get more intense. On a little area of urban land, the investors target to have more gain with tall buildings. Technological developments push the limits of engineering and design. The demand, target, and development feedback each other. Say, as tall buildings get higher (supertall, megatall, etc.) more financial backup is required to afford the technology used offsite and onsite. The Council on Tall Buildings and Urban Habitat (CTBUH) provides a classification for tall, supertall, and megatall definitions. Regarding what to define as tall, CTBUH emphasizes the relative height in the local context and proportion of slenderness; but, clearly defines supertall and megatall. According to CTBUH, a “supertall” is a tall building 300 meters or taller, and a “megatall” is a tall building 600 meters or taller. For example, One Central Park (built in 2013 and designed by Jean Nouvel) in Sydney, Australia, may not be considered tall enough with its 117 meters height compared to the tall buildings in New York, USA. Speaking of slenderness, for example, the Central Park Tower, designed by Adrian Smith and Gordon Gill (who designed the Jeddah Tower) is a fully residential supertall building with 98 stories and 472 meters of height. It is also one of the most slender structures in the world with its slenderness ratio of 18:1. The most slender supertall structure, but not the tallest, was designed by Shop Architects and completed in April 2022 in New York as well. It has a ratio of 24:1 and 435 meters of height (URL11).

The first supertall buildings were built in 1930, the Chrysler Building, and in 1931, the Empire State. The third one was built after almost four decades, John Hancock Centre in Chicago, in 1969 [1]. Since then, the world’s cityscapes are rising year by year. Only in 2019, 26 supertall buildings were completed. Building tall structures has become a matter of power and reputation as the top list of the tallest structures changes year by year. Burj Khalifa in Dubai was completed in 2010 and is currently the tallest building (soon to give first place to the Jeddah Tower in Saudi Arabia, which has no clear date of completion yet) and has the highest number of annual visitors as well, which reaches 16,7 million. Taking into account the average entry ticket fee, it is the most profitable skyscraper[1] in the world (URL 1).

Having said that, as one of the leading skyscraper capital of the world, China banned supertall buildings over 500 meters in July 2021, limited the buildings over 250 meters, and required any buildings taller than 100 meters to fulfill the local fire and rescue capabilities and to consider the spatial scale of the surrounding urban area [2]. Several reasons can be discussed as the cause of this decision. But clearly, tall buildings are a big concern for local fire departments. The rescue ladders are not enough to intervene from the exterior building. The maximum intervention height of the existing fire trucks is about 40 meters and can reach only up to the 13th floor of a building. This is not enough for the contemporary tall buildings, which generally have a hundred floors and more. To gain better insight, China is known for its large number of skyscrapers in cities and Henan is one of them, which has more than 12,900 buildings taller than 100 meters. However, only two special fire trucks in the fire station of the province can intervene up to 100 meters [3]. Hence, both active and passive fire protection measures must be taken inside tall buildings to ensure the safety of the occupants as well as the building. To say, fire safety is not only a matter of controlling heat and smoke for occupants but also must ensure structural durability.

Most of the fire safety measures first intend to prevent fire from occurring and if it occurs, the goal is to prevent it from spreading and to intervene place. If a fire uncontrollably spreads over a wide area, it can be a structural threat to the overall safety of the building and the occupants. Structural safety is a big concern in fire research and development after the disastrous World Trade Centre attack in 2001. Since then, fire safety science and technology have been growing [4]. Structural fire safety design mainly requires the study of the thermal environment caused by a fire, the heat transfer on components’ surfaces, and the structural response to high temperatures. For steel structures, which are known to be vulnerable to fire, the peak can be around 600C degrees for fire-proof insulated components, and 1000C degrees for non-insulated components, which then

[1]Skyscraper is firstly used to refer to buildings with multistories up to 20; but, currently is used in a more generic approach to call all types of unusually high-rise buildings (https://www.britannica.com). This paper uses the terms skyscraper and tall buildings interchangeably.

collapse [5-7]. The measures taken for structural safety can also help to lock fire in one space and give the necessary time to evacuees. Speaking of passive fire protection systems, if a tall building is an office building, compartmentation is very unlikely to apply to the design of floor plans [8]. Rather, fire prevention mostly lies on the active systems (fire alarms, sprinklers, and emergency elevators), and the occupants are expected to be trained in case of an emergency. For residential and hospitality buildings, compartmentation is very applicable to floor plans. However, in residential buildings, the occupants are mostly familiar with the building design, whereas, in hotels, the visitors are short-term users and unfamiliar with the floor plans, which raises more risk in case of an emergency.

Regulations and codes are necessary to provide fundamental fire safety measures. Asia and Middle East countries are the leaders in building high-rise buildings. Hence, they provide a good source of fire safety design issues for tall buildings. The fire code in Hong Kong was first published in 1964, and since then it has been constantly reviewed and revised, particularly after the development of active systems like sprinklers, smoke, and heat detectors. For example, in 1973, automatic sprinkler systems were required for new commercial buildings with more than 30-meter height. In 1987, the requirement was brought for all new commercial buildings regardless of height. Visual fire alarms were brought as a requirement in 1998. A high-rise is defined as any building exceeding 30 meters above the ground floor, according to the 1987 fire code of Hong Kong [9]. This covers a building 100 meter-tall as well as a 484-meter-tall International Commerce Centre. Mixed-use tall buildings have more risks than single (Office) use buildings, considering the combustible materials used for interior decorations, particularly for hotel functions (curtains, wallpapers, mattresses, cushions, etc.). In the USA, as early as 1973, Local Law No.5 on Fire Safety in High-Rise Business was released and although not compulsorily, the Law defined fire sprinklers as acceptable fire protection elements. This change in law happened after some fire incidents cost five lives in New York. However, today sprinklers became one of the main active protection systems regardless of the height and function of the building [10].

Fire safety is related to a complex variety of measures such as spatial distribution of the combustible materials, facade design and material choice, temperature distribution, heat release, smoke composition, air movement and diffusion or ventilation of interiors, and so on. Therefore, today's ambitious tall building designs require fire safety planning specific to the design and have to address all the measures above mentioned [4]. Akashah *et al*. [11] stated that the number of fire incidents in low-cost high-rise residential buildings was higher than any other building type in Kuala Lumpur, Malaysia. They pointed at a variety of reasons including the low quality of materials used, lack of control, and lack of fulfillment of the existing rules and regulations.

This paper focuses on fire safety and prevention measures for tall buildings. Firstly, the facade design of tall buildings is discussed in terms of material choice and detail design. Secondly, fire evacuation planning is analyzed by a review of example case studies. Finally, the fire evacuation scenarios with different parameters are discussed. The paper aims to provide an extensive up-to-date discussion on the fire safety design of tall buildings for architects and to highlight the issues underpinning a successful fire safety design.

2. Facade Design

The facade design of tall buildings is crucial. The facade material can spread the flames and heat. Grenfell Tower was one of the fire incidents which started inside the building but turned into a facade fire with deadly results as the facade material and fault detail design caused the fast spread of the fire to the higher floors. Bahrami *et al*. [12] highlighted the fact that architects and engineers heavily rely on DfMA guides (design for manufacturing and assembly) and the results of simulations to estimate the efficiency of the fire safety design. The latter requires the software or cloud libraries to bring the correct information about the material features so that the final estimations can display real results. Any fault in the flow of the information provided by the manufacturers' datasets regarding the fire resistance of the materials selected in the design can mislead the design process and the fire safety of the building to be constructed.

Speaking of the UK, the tallest building in Manchester city was completed in 2020. The Deansgate Square Project has four towers and one with 67 stories and a 201 meter-tall. The other three have 53, 47, and 40 stories respectively. The tallest tower is also the second-tallest residential project in the UK. The towers were enveloped with a fully glazed unitized curtain walling system and to fulfill the fire safety requirements, a special curtain wall firestop system with perimeter barriers was detailed by the subcontractor. The gap between the concrete floor slab and the external curtain wall system was installed with a firestop system to prevent the passage of fire and smoke between the floors [13].

The trend in the facade design of tall buildings is with glazed facades that need a multidisciplinary approach for ensuring a high level of fire safety. As a desktop study, the design stage should involve any kind of simulations necessary for examining the safety issues including seismic, wind, fire, and evacuation. Minimized model tests in laboratories should follow up to compare the results with the simulations. This method is cost effective and deemed the most effective in the design of tall buildings, which requires precise estimations when it is about safety issues [4]. The facade is not only a building skin to make it look attractive, but also it can be a threat to evacuees in case of a fire evacuation. The use of special glass panes for glazing can be sufficient for ensuring a fire-resistant facade design. However, because of the cost, the fire resistance is often solved only in the spandrel areas, which allows the use of non-fire-rated glass panes for the rest of the glazing. The fire-resistant spandrel area solution is sufficient to prevent the spread of fire through the facade, but non-fire-rated glass panes are prone to overheat and pose the risk of falling in large pieces or bursting into small pieces and becoming dangerous for evacuees and fire rescue teams on the ground floor, and possibly for people in the adjacent room to the bursting pane [14].

The Castle Park View is a tall building Project with 26 stories, which makes it the tallest in Bristol, UK. The contractor claims that all of the materials and details used in the facade design (Stone cladding, inset clay bricks, window panels, and spandrel panels) are fire resistant, being in the A1 Euroclass Standard for fire performance. The original design of the facade included fritted, back-painted, laminated glass spandrel panels to expose the floor levels and the building corners. However, after the Grenfell Tower fire failure, British Building regulations were revised and laminated glass is only allowed for clear-vision glazing within window frames [15]. Current British Standards for the classification of safety classes (BS EN 6206) specify three types of glasses: A, B and C. Class C is wired glass and is considered the type of fire resistant.

Aluminum composite material (ACM) is the most preferred facade material for tall buildings. Dréan *et al*. [16] stated that ACM cladding is the most important element driving global fire behavior of the facades. Therefore, in one of their studies, they investigated the performance of three different qualities of ACM under fire loads. ACM with a polyethylene core, despite the foil processed with poly-isocyanurate, reached a higher heat release rate than the ACM with a polyethylene core and wool insulation behind in 2 ½ minutes. The best result was received from the ACM with an A2 mineral core and foil processed with poly-isocyanurate, which reached the peak heat release rate in 8 ½ minutes. They also highlighted that ACM with polyethylene core quickly burns out the material as well. In addition, it contributes more than 90% of the peak heat release rate and the total energy release.

Facade fires in tall buildings happen in increasing numbers. Facade fire is critical as it can speed the radiation of fire heat, smoke, and flames to upper floors. It can be life-threatening in many ways. To say, compartments are passive protection systems that are planned mainly for internal incidents. A facade fire can leak into the floors from any gap, e.g. through facade openings or joint details in poor quality on the facade structure [17]. Therefore, much more attention must be given to the detailing of the facade structure.

3. Fire Evacuation Planning in Tall Buildings

Egress means “a continuous and unobstructed way of exit travel from any point in a building or structure to a public way", and consists of three main parts: the exit access, the exit, and the exit discharge (as described by the U.S. Department of Health and Human Services). Stairs are the primary elements of the egress arrangement and different estimations are done depending on the national codes of countries. *Stairs* can be a part of a route for complete evacuation or can be arranged to serve as a staged evacuation of several floors (Dewan, 2022). To say, the flow of the occupants' evacuation from stairs can slow down due to the accumulation of busier floors. This happens particularly when emergency stairs are not properly estimated and designated in the floor plans, which dangerously affects evacuation time and success. Notwithstanding, fire evacuation planning cannot only depend on the use of staircases, considering the number of floors and thousands of evacuees. For a mega-tall building, daily users can reach and be over 25,000 [18]. Thus, for tall buildings, elevators play a significant role in evacuation planning [19].

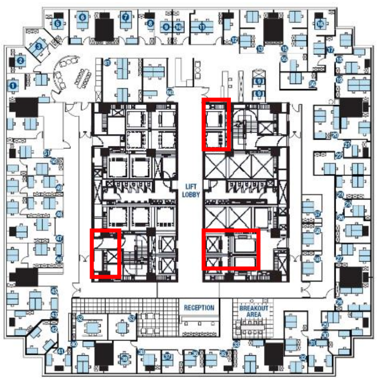
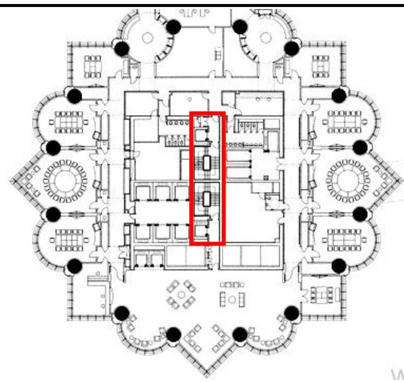
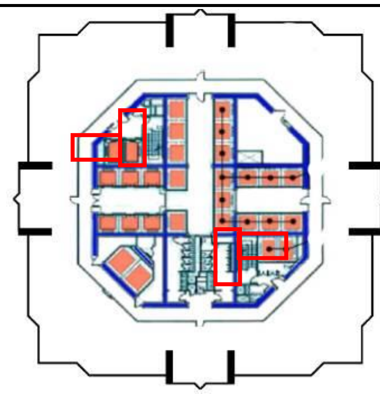
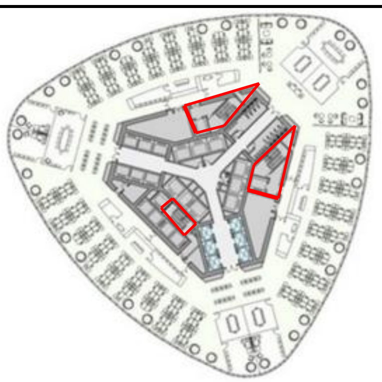
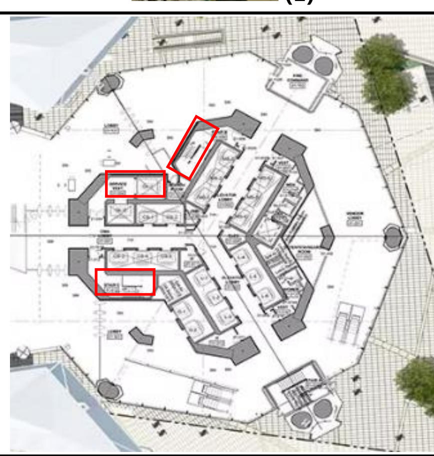
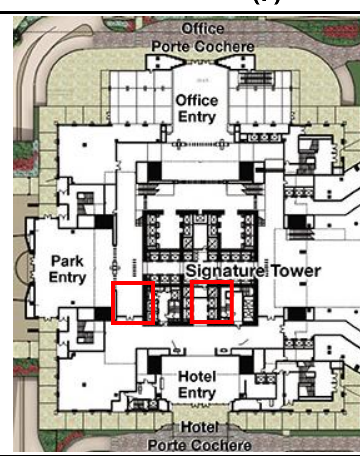
Elevators can be dangerous for fire evacuation if not well-designed with supporting mechanical systems. In the evacuation, the elevator will move downwards and negative pressure borne will suck fire smoke rapidly, which can cause deadly results [20]. In addition, for tall buildings, the rentable floor area is very precious, thus the design of the core is often squeezed into the smallest possible area. This means, elevators for different uses are located in the same area and much more attention is needed to direct the evacuees correctly. Smoke and fire remote control systems should be maintained well. An unfortunate disruption may cause deaths. For example, in case of a fire, if people get caught in one elevator and the doors are not opened to flee or if the elevator is not automatically redirected to the safe floors, people can expose to the fire smoke or flames.

Refugee space is often designed as a part of a phased evacuation and is usually adopted for supertall and megatall buildings. The design of refugee space is complex. It should have a sufficiently large space and no less than half of one sqm per person. The walls should be insulated with 120min. fire resistance material with certain smoke seals. As active systems, the refugee space (often a room and sometimes a floor) should be provided with smoke ventilation with an air-pressurization system and should be two-way communicable through the building fire control center. It should be accessed through separate elevators – emergency elevators or express elevators- and connected to the fire staircases [21]. Hong Kong's local fire code requires planning a refugee space in 50% of the floor area on the designated floor, and a refugee floor is considered a part of the egress route for buildings with more than 40 stories. In other words, a refugee floor can provide an alternative route or a redirected route to another staircase if the first choice of the staircase is loaded with smoke or just to prevent the stampede in one route [22]. Lau *et al*. [22] surveyed 51 tall buildings in Hong Kong. Among them, 15 were non-residential and their height varied from 166 meters to 484 meters. Seven of them had one refugee floor, of which height reached around 200 meters. The tallest two of the non-residential buildings, reaching 484 meters, had four refugee floors. Among 36 residential tall buildings they surveyed, only one had three refugee floors, of which height was a little shorter than 200 meters. The majority had two refugee floors and their height varied from a little less than 150 meters to a little less than 250 meters.

Fire evacuation is a complex issue for tall buildings. Several floors, the function, and the occupants' features build the complexity in the life and fire safety design of tall buildings. Because of this complexity and the uniqueness of each tall building design, more preventive measures are necessary than the basic requirements given in the national and local codes. Unlike in conventional buildings, the egress arrangement may include staircases, emergency elevators, evacuation shuttles, refugee floors, and sky bridges. Furthermore, other than complete evacuation, the evacuation plan of tall buildings can be managed as partial evacuation, staged evacuation, retarded evacuation, and defense in place (no evacuation) (Dewan, 2022). As a conventional approach, complete evacuation is simultaneous evacuation and all occupants are urged to egress at the same time. Differently, phased evacuation urges the egress of occupants under direct danger and requires others to remain in place for later egress, if the dangerous condition is still on. Phased evacuation, thus, requires well-estimated planning and organized management not to cause any harm to occupants. Phased evacuation also helps to save more net floor area in some cases [21]. To understand the approach in the fire safety design of tall buildings, eight examples of supertall and megatall buildings are examined below and in Table **1**.

Taipei 101 is a supertall building of 508-meter height. The building has 84 floors effectively used by occupants. The building has two transfer floors; one is between the 35th and 36th floors and the other one is between the 59th and 60th floors. The building is also one of the tall buildings designed with double-deck elevators to speed vertical transportation. In total there are 61 elevators including high-speed elevators, emergency elevators, cargo elevators, underground parking elevators, and general passenger elevators. There are two staircases with pressurized air systems and the occupants can reach stairs and emergency elevators through also a pressurized air egress hall on each floor. The occupants are expected to flee through this hall first and to reach a refuge space designated on every eight floors of the building [20]. Wu and Mizuno [23] examined a simulation for mass evacuation from Taipei 101. For 12,200 occupants it took 96,67 minutes to evacuate and in case of all occupants flee at the same time, the staircases can discharge 65 people per minute at most.

Table 1: **(A) Taipei 101, Taiwan; (B) Petronas Towers, Malaysia; (C) Jin Mao Tower, China; (D) Guangzhou International Finance Center, China; (E) Capital Market Authority (CMA) Tower, Saudi Arabia; (F) Signature Tower Jakarta, Indonesia (URLs). The emergency elevators and staircases are shown in red.**

 **(A)**	 **(B)**	 **(C)**
		
 **(D)**	 **(E)**	 **(F)**
		

Petronas Twin Towers are two megatall buildings with 88 stories, which have four refugee floors, two per each building. Both together have two-stage evacuation planning for their nearly 10,000 occupants. Evacuation is set up in three different levels of emergency; minor, major, and crisis, respectively. Stage-one evacuation is the phased evacuation and complete evacuation follows as the stage-two evacuation. As the towers are linked with a sky bridge on the 42nd floor, the 37th and upper floors use the emergency lifts to take the sky bridge and to transfer the other tower, which is not on fire, to evacuate the building safely. From the basement floors and up to the 37th floor, the occupants must use the stairs and elevators to evacuate directly. The target time for the total evacuation time is one hour at most [24].

Jin Mao Tower has more than 130 elevators and two of them only serve the observatory deck for daily visitors. These special elevators can speed up to 9 meters per second and it takes only 45 seconds to reach the observatory deck on the 88th floor from the ground floor. The office zone from the 3rd floor to the 52nd floor is served by 26 elevators that are split into five vertical zones. A shuttle and 10 service elevators run between the 53rd floor and 87th floor, to serve the hotel zone. There is an atrium between the 56th floor and 87th floor, thus the elevator core is split into two parts serving at both ends of the atrium. There are refugee floors on the 15th and 30th office floors, and refugee spaces are located on every guest room floor.

Guangzhou International Finance Centre (IFC) is a supertall building with 13 floors and 432-meter height. The building has multi-functions split into two main parts. 69 floors serve as office spaces and the upper 34 floors serve as a luxury hotel with a large central atrium, which makes the unique interior design of this supertall. In consideration of a malfunction in the fire control system, water tanks for the fire cooling and extinguishing system (fire hydrants and sprinklers) are located on the roof to ensure the flow of water into the lines by gravity, if the pumps fail to work. Besides fulfilling the fire safety code in China, the building is planned with further fire safety enhancement. For office floors, three staircases and for hotel floors two staircases were designed. The widths of the stairs were adapted according to the occupant load instead of being the same width throughout the building. In the floor plans, the travel distance to a safe zone (e.g. fire-protected staircases) is kept within 30 meters. Active fire protection systems (sprinklers and smoke control systems) are installed throughout the tower. Also, refugee floors are designated on every 17 floors for the office zone and every 19 floors for the hotel zone. The hotel atrium is the attractive design element; however, atriums become chimneys in case of fire. Thus, fire shutters are located to separate the restaurant floors, between the 71st and 72nd floors. In addition, the room walls facing the atrium after the 73rd floor are built as fire-rated walls and doors. Mechanical smoke extraction systems are utilized for the atrium as well. To say, an atrium is one architecturally attractive element but always comes with a price. The estimations for the total evacuation time to the refugee floors vary between 11 minutes and 24 minutes, at maximum. The occupants between the first floor and the 12th floor are planned to evacuate directly out of the building [25].

Atrium design as big as in Guangzhou International Finance Centre (IFC) requires a detailed provision of a fire and smoke control system for ensuring safety at a certain level. The atrium is highly preferable from an architectural standpoint. However, higher fire safety cost compared to a higher risk to occupants weighs over and makes it less preferable in most architectural designs. This means a trade-off between these two issues needs to be clarified and agreed upon by not only the architect but also the contractor and the engineering team responsible for the project at hand [26].

Capital Market Authority (CMA) Tower has 80 stories and reaches 385 meters. The tower largely provides Office spaces along with additional functions (swimming pool, fitness center, auditorium, cafeteria, etc.). The design of the tower was handled in three parts; low-rise, mid-rise, and high-rise to better design the building systems such as vertical transportation, mechanical and electrical systems, and fire protection systems. The 22-meter-tall atrium rises from the entrance level of the tower. Vertical transportation is similar to Taipei101, as the escalators on the ground floors mainly serve the use of double-deck elevators. To achieve a good ratio of 70% on 2500 sqm gross area, the optimal design of the core was critical. Single-deck and double-deck elevators are used together with a twin elevator system, which is a technology that enables two elevator cabins to travel separately in one elevator shaft. In the low-rise and mid-rise levels of the CMA Tower, 24 twin elevator systems were used to serve 50 floors in only six elevator shafts. In addition, 12 double-deck elevators were used as shuttles for the same levels. This helps to save more net areas in the floor plan [27].

For the capital city of Indonesia, Jakarta, a megatall building –*Signature Tower* - was proposed with 111 floors and reaching 638 meters in height. The building had mixed functions; a 6-star hotel, rentable office spaces, a shopping mall, an entertaining podium, and a conference center. 9 refugee floors were designed with intervals varying between 9 and 12 floors. They mainly were located on the mechanical and service floors and refugee spaces were built in 2-hour fire resistance materials. One fire-evacuation staircase was planned in 142,5 cm in width and along with a pressurized air shaft. A refugee floor serves all the occupant load of the floors until the next interval and provides sufficient space by meeting 0,4-0,5 sqm per person. A complete evacuation scenario estimated the total time of evacuation in 2 ¾ hours [28].

Libeskind Tower in Milan, Italy, is an office building with a concave bending through its 28 floors reaching 175 meters in total (Fig. **1**). Mazzucchelli *et al*. [4] developed the fire safety analyses of the tower and tested three scenarios. Scenario 1 is that a fire begins near a Standard response sprinkler; Scenario 2 is that a fire begins near a quick response sprinkler; and Scenario 3 is that a fire begins near a sprinkler failed to work, which to tests the smoke and heat invasion in the room and the role of the release from the facade. The temperature distribution on the facade reached its highest value in 10 minutes, over 600 °C.

Figure 1: The floor plan of the Libeskind Tower in Milan, Italy, and its view from the outside [4].

Absolute Towers project in Canada has two towers; one with 56 floors and is 176 meter-long, and the other one with 50 floors and is 158 meter-long. The originality of the towers comes from their rotating form. Each tower rotates from the ground floor to the top floor between 200 and 209 degrees, which is possible by rotating each floor by 4 to 8 degrees [29]. The core of the tower plan has six elevators, and three of them (shown in red color in Fig. **2**) are barrier-free elevators, which are designated for the use of disabled people and their evacuation in case of an emergency because the building is residential. The remaining three elevators are for normal use. There is one staircase in the core and separated by fire-shut doors from both sides of the doorway.

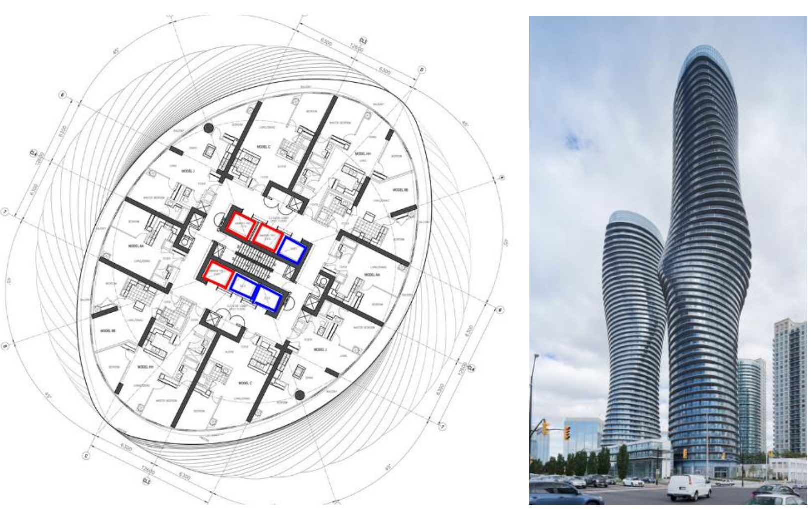


Figure 2: The floor plan of the Absolute Towers in Mississauga, Ontario, Canada, and its view from the outside; designed by MAD Architects (URL 2).

The future's tallest building, Jeddah Tower has a different evacuation plan than the usually adopted phased evacuation. The Lifeboat Evacuation plan uses high-speed shuttle elevators and with all estimations, the total evacuation time for this megatall building is less than two hours [1]. Li and Reiss [18] discuss the challenges of life and fire safety in tall buildings. Daily, a tall building hosts hundreds or thousands of occupants, who consume water. Accordingly, water conservation turns out to be one of the main sustainability goals and also a key to ensuring a reliable and cheap fire suppression system. In Burj Khalifa, the water storage tanks are located above the sprinkler and standpipe systems per sections to feed the pipes with water simply with the help of gravity, so that no malfunction would disrupt the fire suppression system.

As seen from the examples, many alternative architectural and structural solutions for the forms and the height of the buildings have been applied and the limits of design have been pushed hard. This means many different possibilities of fire spread, evacuation, and firefighting difficulties from the standpoint of fire safety [26].

4. Fire Evacuation Scenarios

4.1. Estimation Models

There is numerous software to test evacuation models for buildings and tall buildings. Some of them are rather suitable to reveal the effect of elevators in egress; some of them are not appropriate to work flexible scenarios, like more than one egress route for occupants; and, some of them do not take into account the variety in features of the occupants [8]. This section aims to uncover how the estimations for evacuation planning vary based on the different scenarios and inputs that affect the results.

Gravit *et al*. [30] investigated the role of elevators in the total time of evacuation by modeling 20 – 30 – 40- 50- and 60-story buildings. They estimated the models with 100 people per floor and also included shuttle lifts for 40, 50, and 60-story buildings. The resulting comparison revealed that the total time of evacuation was 32% shorter through a combination of stairs and elevators for a 60-story building than the evacuation through only stairs. The difference was 34% for a 50-story building and 29,5% for a 40-story building. The difference for a 30-story building was 27,8% and nearly doubled the difference for a 20-story building, which was 15,3%. This explains how elevators and express lifts shorten the total evacuation time in case of an emergency, although the study did not take into account the people with different paces and mobilities.

Human flow density of more than 7-8 people/sqm can cause chaos and serious injuries [31]. From this point of view, [31] simulated the effect of the width of the staircase and corridors. Based on their results, for the number of occupants more than 35 per floor, a width of 90 cm for the staircase exceeds 7 people per sqm, thus resulting in unsatisfactorily. A width of 105 cm and more results satisfactorily. However, a staircase of 150 cm in width resulted satisfactorily until 50 people per floor, and the results were unsatisfactory after exceeding 55 people per floor. In addition, the evacuation time was shortened by 11% for the staircase with 105 cm and 31% for the staircase with 150 cm compared to that for the staircase with 90 cm and the models with 55 and 60 people per floor.

A report by NFPA [32] examined the performance of various evacuation scenarios on a model of two identical twin towers with 50 stories per each and linked to each other with sky bridges at different floors. The scenarios include the single and combined use of egress components, such as stairs, elevators, transfer floors, and sky bridges. Transfer floors were designed on the 18th and 33rd floors in each tower model. The model included shuttle elevators with 24 people capacity. The stairs were modeled according to the basic code requirements, 112 cm in width. However, it is necessary to highlight that the NFPA 101 Life Safety Code requires stairs expect occupant load of more than 2000 to be designed 142 cm in width. The scenarios that included only the elevators, emergency lifts, and transfer floors gave the shortest time to evacuate the whole building. The scenario included only stairs expectedly gave the slowest time. The scenarios included both stairs and elevators with different other egress components resulting in pretty close and medium results.

Using emergency lifts and defining elevators as a part of the egress route particularly makes a difference in tall buildings. Gravit *et al*. [33] modeled a 60-story building with 100 people per floor. The model had six elevators for daily use and four emergency lifts for 26 people to transfer at one time. They concluded that using elevators along with stairs as an egress route in a 20-story building decreased the total evacuation time by only 6 minutes. However, for a 60-story building, the decrease was by 32%, which takes 16 minutes. This reasonably showed how a well-planned elevator system can help speed and safe evacuation from a tall building.

Phased evacuation - staged evacuation – should not be taken as an evacuation accelerator [34]. It does not shorten the total evacuation time but guides to safer evacuation planning. A three-stage evacuation plan was tested on a 20-story building with 100 occupants per floor. The fire was set on the 9th floor and the evacuation was started at the same time from the floor. Meantime, the 1st and 2nd floors were set to evacuate as well. Then, every two floors were set to evacuate within 20 seconds. The model estimated almost 11 minutes to complete the evacuation in the whole building [34].

4.2. Human Behaviour in Fire

Evacuation modeling mainly lies in the investigation of the capacity of the preventive infrastructures of the building, and the occupants' behavior follows. However, the modeling should include a wide spectrum of occupants, such as the number of children (for residences), pregnants, old people, disabled people, people with different weights, and people less familiar with the building, i.e. daily users, tourists, etc., which affect the evacuation route and time success. The studies also have focused on the fire safety design of buildings, rather than the behavioral features of the occupants [8]. Having said that, the occupants’ choice of egress element is a serious issue that may affect the evacuation time and success. In a tall office building it should be taken into account that occupants in panic tend to prefer the nearest elevator or stairs. This can increase the estimated load of the staircase and the traffic of elevators between floors and the exit. Repetitive training in fire evacuation planning, therefore, plays a key role in the success of the evacuation. Otherwise, despite all of the fire safety measures being taken into account, the occupants who do not behave as trained will fail all of the hypothetical estimations done. It also should be noted that healthcare buildings require particular attention considering the infrastructure of the building (the ventilation, electrical equipment, the medical gases in lines, etc.) and the vulnerable occupants (elders, children, pregnant, people with temporary or permanent disabilities, etc.). Hence, this type of building necessarily urges further fire safety measures to take and must consider the behavioral features of the special groups (Dewan, 2022).

Ding *et al*. [35] analyzed the occupants' behavioral effect on the speed of evacuation on a 28-story building with one staircase and two elevators by simulating scenarios composed of 20 young-aged, 20 elderly (slow-moving), and 20 middle-aged people per floor. They concluded that preferring young-aged and elderly to evacuate through elevators speeds up the total evacuation time and also prevents the accumulation on the stairs. In addition, preferring the evacuation of the lower floors before the upper floors provide more efficient evacuation performance. Zhang *et al*. [36] highlight that the occupants' behavior in a nighttime emergency evacuation is affected by spatial perception factors such as accessible design, signage facility, and emergency lighting system, risk perception factors such as level of fear and level of perceived influence, and social network factors such as kinship network, neighborhood network and organization network within the community.

Virtual reality (VR) is one cost-effective method to research human behavior and has been used in various scientific fields such as psychology. Andrée *et al*. [37] were one of the first appliers of VR in understanding human behavior in fire. In their study, a 35-story mixed-use tall building was modeled to understand the first choice of the evacuation of participants, the waiting time for elevators, and the effect of using flashing green lights in directing evacuation. The majority of the participants chose the elevators as the first choice when flashing green lights were used. The experiment also showed that evacuees were impatient to wait longer than 5 minutes for elevators. The participants who kept waiting for less than 15 minutes stated their feelings as stressed, anxious, insecure, etc. The evacuees who saw the elevators passing the 16th floor without stopping, which the fire was modeled after, reconsidered stairs to the exit, which needs certainly further study to understand the likeliness of such behavior in a higher building fire.

Arias *et al*. [38] did research through VR fire simulation to understand the evacuees' choice of exit. A fire on the ground floor of a two-story house was modeled and the smoke spread down the stairs and slowly to the upper floor. Participants mostly preferred to jump out of the window. In real life jumping off from a 3-4 meter height would not be a big deal, but it was the first choice of most as a fire exit. Lately, Wang *et al*. [39] explored the occupants' wall-following behavior through a VR fire evacuation game. To understand the role of vision in wall-following behavior, three levels of the smoke environment were created: slight smoke, moderate smoke, and dense smoke. In the dense smoke, a dark black smoke spreads around the scene that players lose their vision. Expectedly, dense smoke caused the participants to rely on the wall lines than the slight and moderate smoke environment. Participants unfamiliar with the plan also relied on the wall-following behavior to find an exit, while the participants familiar with the plan displayed far less reliance. Familiarity with the plan and the smoke density were found irrelevant, while both had affected the wall-following behavior of the participants.

With the development of smart technologies, fire evacuation estimation models and evacuation design evolves too. For example, Balboa *et al*. [40] developed a real-time intelligent evacuation guiding system and tested participants to understand the effect on the behaviors of evacuees. The overall result was better in terms of finding a better and shorter way to exit the building. Sheeba *et al*. [41] proposed a highly mathematical model with petri nets for the fast fire evacuation time by considering the pre-evacuation time and the human behavior constraints as the factors that negatively affect the total time for evacuation. As understood, human behavior involves a complex factor in the estimations of a fire evacuation. Considering the real-life worst-case scenario, the range of occupants surely includes diversity in physical features and age ranges (particularly for tall buildings with shopping floors and hotel floors) that mainly affect the estimations resulting without considering such factors.

5. Conclusion

Fire safety in design is often thought of secondarily or auxiliary. Abiding by the fire safety codes is often deemed sufficient, but as the discussion thus far highlighted, for tall buildings it is complicated in terms of deciding how hundreds or thousands of people will evacuate safely. Passive fire protection systems should not be designed only at the basic level by how defined in the codes. The exhaustive review showed that even the small changes in the width of stairs and doorways are critical for the evacuees' escape. Active fire protection systems should be supporting passive fire protection systems, as seen in the examples with refugee floors. As tall building design is widespread all around the world, each building has its unique fire safety solutions. As much as the generic approaches, these unique solutions keep guiding to a better solution for the next tall building. In the meantime, fire safety science and technology are growing up. Several studies provide a good source for understanding the effect of different fire evacuation plans depending on the building height and further parameters. Besides, some researchers examine their extraordinary fire escape solutions. For example, Zhang *et al*. [42] radically proposed spiral slides and shunt valves for fire evacuation, which needs further examination in the future for sure. Fire safety is not only an engineering problem to deal with, but also architects must know the holistic approach in the fire safety design of tall buildings since it involves their architectural design as well. The examples laid out how the architectural design of the core, the decision of having an atrium, and the choice of facade detailing and cladding material can be effective in fire safety planning. This paper, is hoped to provide insights into the fire safety design of tall buildings and highlight the issues to bear in mind, such as human factors in evacuation, to achieve a promising fire safety design.

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