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A REVIEW OF DESIGN PARAMETERS FOR SAFE EVACUATION IN HIGH-RISE BUILDINGS

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Abstract

Lack of empty areas in cities and demand for new spaces lead people to increase the number of floors in accordance with developments on the technology. Increase of high-rise buildings brought along problems such as evacuation. Evacuation of high-rise buildings is a complex research area with numerous diameters. In this paper, the literature on evacuation of high-rise buildings is reviewed with the purpose of revealing the point reached in high-rise egress and design considerations to establish a safe egress during emergencies. The literature is reviewed, analyzed and classified under these considerations. It is seen that future research is needed on evacuation via elevators, fatigue effect and human behavior. Also, being Turkey the 4th city with most skyscrapers in the world and being the literature on the topic is quite limited in Turkey, show the importance of the topic.

1. INTRODUCTION

Need for spaces, especially for business and residential purposes, lack of empty areas in cities, and developments on the technology lead people to increase the number of floors. 3 main developments that affected the high-rise buildings can be listed as; development of the safe elevators (1853), production of steel frames and development of air condition systems [1].As a result, the first high-rise buildings in the USA was built from 1884 to 1939 [2]. As time passed number of high-rise buildings increased and for Turkey, Istanbul became the 4th city with the most skyscrapers in the world [3].
Embodying high number of occupants makes it more important to successfully evacuate high-rise buildings during emergencies. To measure and evaluate the effectiveness of a building's evacuation, evacuation time needs to be investigated. Required safe egress time (RSET) and available safe egress time (ASET) must be identified and make sure that RSET is shorter than ASET. The use of evacuation models makes it easier to identify these parameters since evacuation drill may not always available for safety concerns etc. In accordance with building occupancy type, building characteristics and occupant characteristics, egress strategy can alter. For an efficient evacuation strategy, evacuation timeline must be considered.
Architectural design of the building significantly effects the evacuation process. In the design stage, occupant load must be calculated to be able to set other components such as egress strategy, evacuation timeline and exit capacity etc. After occupant load is determined, exit capacities can be calculated according to occupant load.
In this paper, evacuation timeline, simulation models to calculate evacuation timeline, evacuation strategies and egress components from literature for high-rise buildings are reviewed.

2. BUILDING EVACUATION

Certain emergency situations that people experience lead researchers to study on effective evacuation of the buildings. Experiences on this field show that evacuation timeline is related to egress strategies and

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human behavior. The relationship between these evacuation components is explained in the following subsections.

2.1. Evacuation Timeline

Evacuation timeline is an important part of the subject of evacuation of buildings. Numerous drills and accidents lead researchers to classify different components of evacuation process. Although different researchers [4–12] investigated the timeline of evacuation process with different levels of detail, general approach to this subject is to divide evacuation process into pre-evacuation time and evacuation time [3].
Pre-evacuation time defines the time interval between the alarm and the first movement to evacuate the building [8,9]. Pre-evacuation time can be very effective on evacuation timeline since it may take longer than evacuation (movement) time, especially for low density buildings [8,9].This is because for this type of buildings, it may be harder for occupants to communicate with other occupants who do not aware of the emergency. McConnell et al. analyzed recognition time and response time, which are phases of pre-evacuation time, on the event of 9/11 attack [10]. Pre-movement time is related to human behavior, which is discussed in latter section, therefore it is the most unpredictable phase of the evacuation process [8]. Since pre-evacuation time is hard to calculate, Lovreglio et al. built a database consist of 9 fire incident and 103 drills [8]. Thus, the database can be used on evacuation simulations as an input.
Movement or evacuation phase stands for the time interval between the first movement to evacuate and the last person to reach the exit [13]. This phase has a more physical characteristic since it involves occupants' movement. Engineers mainly researched the fundamental factors associated with movement time since they are calculable elements. Factors affecting movement time can be listed as; characteristic of stairs (bottlenecks), physical characteristics of occupants', fatigue effect, grouping effect, merging effect, counterflow and congestion [14].
Movement time and pre-evacuation time constitute total evacuation time (TET) [9] as can be seen in Figure 2.1. RSET and ASET is two main definition to evaluate the safe egress for buildings. ASET stands for the time interval between the ignition and the establishment of conditions that human body cannot tolerate [15]. RSET is the time required for all occupants to reach safe area [16]. RSET constitute of detection phase, notification phase, pre-evacuation phase and evacuation phase [16]. Being RSET is shorter than ASET is an important check point otherwise occupants may hurt during evacuation process. Evacuation timeline, as can be seen in Figure 2.1, can be defined as a complex chain of events starting from ignition. The rescue/evacuation must be ended before untenable conditions (visibility, temperature and toxicity) occur.

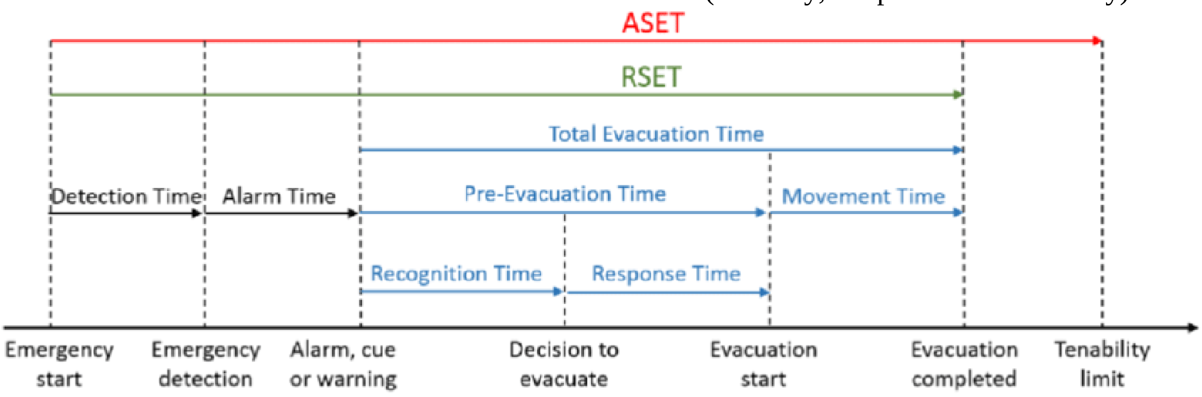

Figure 2.1.Evacuation Timeline (Adapted from [7])

2.1.1. Approaches to Evacuation Time Calculation

Although there are some back-of-the-envelope (hand) calculations to assess evacuation, performance-based approach is becoming more widespread [18]. For example, SBR Regulation in Netherland requires occupants to reach safe areas 1 minute after alarm and for clearance time, it adds 90 seconds for every segment higher than 50 meters [19]. These calculations used to clarify the egress time for buildings generally. However, calculation of egress times with performance-based calculations, allow safer solutions for different buildings.

With the advancement in technology and wide spreading the use of performance-based calculations, the use of computational models is expanding in our lives. Evacuation models generally designed for optimization, simulation and risk assessment [20]. This section mainly evaluated the simulation use of computational models. Simulation models, beside other advantages, make it easier for users to evaluate the effectiveness of evacuation of buildings. Since evacuation drills may not be available or safe for some buildings, modelling and simulating the evacuation is easier, cheaper and safer.

Egress models use 3 different strategies to evaluate the evacuation of buildings. One of these models is Coarse Network Model which is the most basic and oldest one. This model divides the building into rooms, corridors and stairs to model the evacuation process. Secondly, Fine Network Models divide floor plan into grids (square cells according to human body measures) and finally Continuous Network Models allows occupants to move between starting point to exit point with the flexibility of more complex routes [18]. With technological developments and increase of computer performances, the use of continuous network models and number of continuous network models increased [21].

Evacuation simulation programs are divided 3 groups in terms of modeling method; behavioral models, movement models and partial behavioral models. By contrast with movement models, behavioral models are capable of assigning behaviors to occupants. [18].

Olenick et al. evaluated the models for fire and smoke into 6 sections [22]. These are; zone models, field models, detector response models, egress models, fire endurance models and miscellaneous models. Zone models evaluate effects of fire in a defined zone. Although zone model divides a compartment into two zones, field model is able to divide thousands of zones and calculate the effects. Detector response model estimate the activation process of detectors. Egress models, which were mentioned above, simulate the behavior of occupants and lastly fire endurance models simulate the building components' fire endurance. [22]

Two simulation models classified in terms of occupant perception are macroscopic and microscopic models. Microscopic models are able to assign individual behaviors to occupants and macroscopic models consider occupants as a group of people with same characteristics [23]. Control volume model and Takahashi models are some examples of macroscopic models that calculate the evacuation process with fluid dynamics. Since large number of models may lead users to have difficulties to select the right model, Ronchi and Nilsson assessed the verification and validation of evacuation models for an easy use and selection of evacuation models [24].

2.2. Egress Strategies

The main purpose of egress strategies is to supply the safest evacuation for occupants to reach the exit. This purpose requires different approaches for different occupant types and building types. 4 egress strategy widely accepted are; simultaneous full building evacuation, protect-in-place, relocation and phased (or partial) evacuation [6].

Simultaneous full evacuation which is considered the most common one is a strategy that purpose to evacuate whole building with same alarm [1]. As it can be seen in Figure 2.2, all occupants are expected to evacuate the building simultaneously. Protect-in-place strategy can be used for incidents that full evacuation may take too much time and fire fighters may be able to focus on extinguishing instead of evacuating the building [7]. As it can be seen in Figure 2.2, it is used in conditions that the fire (or emergency situation) is controllable without occupants getting hurt. Relocation strategy is used to move occupants from hazardous area to safe areas like refuge area or other safe areas [6]. It is especially useful for elder, sick and pregnant occupants. Deeper discussion on this subject is given in section 3.2.3 about advantages and disadvantages of relocation strategy and use of refuge floors. Lastly, phased evacuation may occur in 2 ways; compartmenting in same floor, compartmenting in different floors. As it can be seen in Figure 2.2, first the occupants who are closer to the fire must be evacuated to avert an injury.

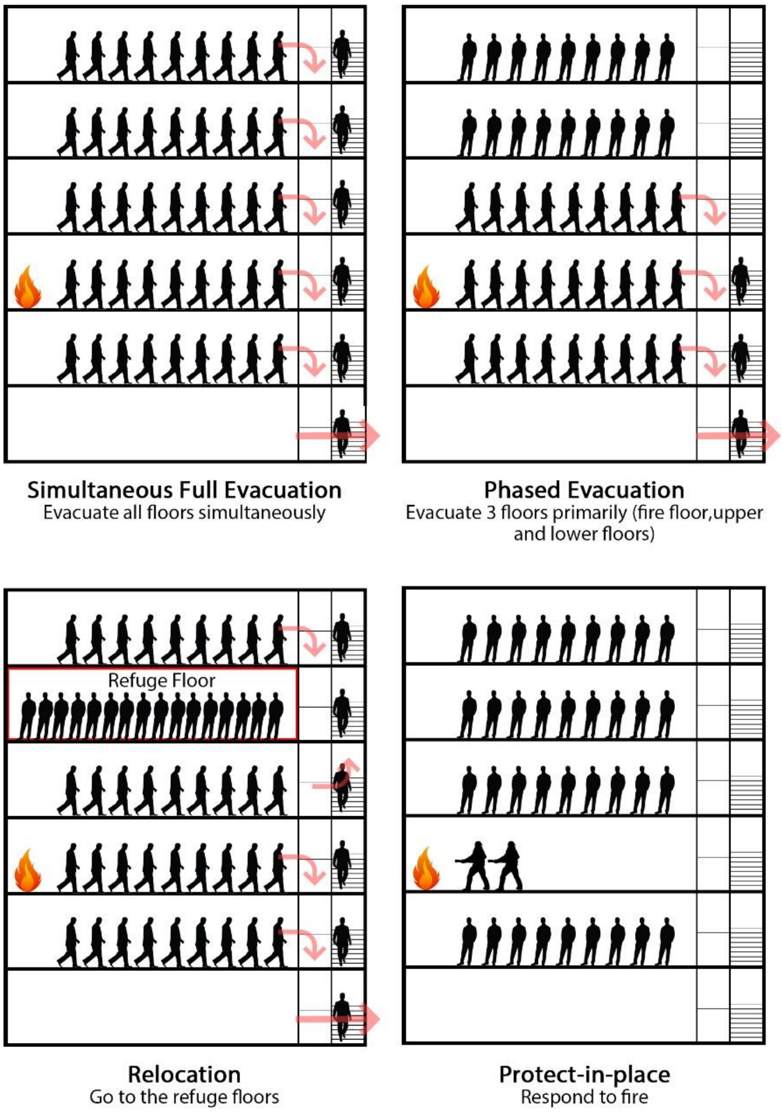

Figure 2.2. Egress Strategies

2.3. Human Behavior

Understanding the human behavior has a crucial role in providing an effective evacuation [25]. Although there are a lot of researches on human behavior during emergencies, there are still blind spots and misinformation (e.g., contrary to popular belief, the researches showed that the human behavior during an emergency is not dominantly consist of panic [26].)

Human behavior comes after the decision making. The decision-making during an accident happens by two ways; automatic system and reflective system. While automatic system provides fast and uncontrolled decisions like taking the daily commute, reflective system provides slow but controlled decisions [26]. Some factors affecting human decision-making during emergency situations are given below.

During emergency situations, occupants' decisions affected by risk perception. Risk perception is directly proportional to willingness to act [27]. The more threatened one feels, the more willing he is to act. On the contrary, "normalcy bias" lead occupants to underestimate the threat and generally makes it longer to start the evacuation [26].

Data extracted from evacuations indicate that occupants firstly tend to investigate the alarm if it is false or not. After understanding there is something unusual, people generally contact with family or close friends and before beginning to evacuate, they take personal belongings. These behaviors generally make it longer to evacuate and have an important effect on evacuation time. [28]

While evacuating the building, human factor affects evacuation time. Researches showed that the leading person determine or limit the walking speed of occupants behind him. This situation is called platoon effect. Platoon effect is the slowing effect composed by a person with slower velocity than occupants behind that person [14].

When drills and evacuations analyzed, it is observed that occupants generally tend to evacuate the building via stair that they last used or most used [29]. This situation occurs especially on occupants who are not familiar to the building. Considering 51% of the evacuees of WTC attack indicated they never used stair before [30] and Gershon indicated that the past experiences important to motivate occupants to move [21], the importance of drills and education can be seen.

Lastly the panic behavior has a negative effect on evacuation. Lin et al. conducted an experiment to investigate faster is slower effect. It is observed that when occupants are frazzled, evacuation time extends [31].

3. EVACUATION of HIGH-RISE BUILDINGS

The term used by most countries 'high-rise building' or 'tower blocks' in England means a multi-story building [32]. Evacuation of high-rise buildings is more important than low-rise buildings since they generally consist more people [32] and the fact that Istanbul is the 4th city with the most skyscrapers in the world [3] shows the importance that should be given to this issue in Turkey. Evacuation of high-rise buildings is different from low-rise buildings as can be seen in Table 3.1 which summarizes the differences of high-rise building in contrast with low-rise buildings in terms of evacuation. Some of the differences and specific requirements for evacuation of high-rise buildings can be listed as; increasing number of occupants, increasing the merge effect with the increase of number of floors, increase of required evacuation time, the use of refuge floors and occupants being tend to use elevators because of habits [32,33]. While the building rises, it is getting harder to reach the area to provide assistance [32]. The chimney effect and stack effect are some other factors make it harder to fight high-rise building fires [34,35].

Table 3.1. Factors Effecting High-rise Buildings in Contrast with Low-rise Buildings in Terms of Evacuation

•Consisting more occupants
•Increase of merging effect due to increase of floors
•Increase of evacuation time due to longer exit paths
•Use of refuge floors
•Occupants being tend to use elevators because of habits
•Getting harder to reach the area to provide assistance
•Chimney effect
•Stack effect

There are numerous researches conducted to find an optimal solution to evacuate high-rise buildings. Zhong-an et al. indicated that although evacuation from top to bottom floors extend the evacuation time, it makes evacuation safer since congestion does not occur [36]. Some elements related to evacuation of high-rise buildings are discussed below.

3.1. Design Considerations

Building safe buildings in terms of evacuation, require some considerations. Defining occupant load and exit capacity at the design stage of the buildings, make it easier to plan emergency evacuation strategy for the building. Mentioned design considerations avert difficulties after the building is constructed.

3.1.1. Occupant Load

Occupant load is defined by NFPA as the total number of occupants that may be in the building at any given time [37]. Defining occupant load makes it easier to lead occupants to safe areas with right strategy.

Occupant load factor is given in NFPA 101 (Table 7.3.1.2) [37] and in International Building Code (IBC) (Table 1004.5) to indicate the occupant load for different occupancies [38]. Turkey's Regulation on Fire Protection defines occupant load factors in Appendix 5/A [39].

3.1.2. Exit Capacity

Number of people that can pass through a given opening in 1 minute is defined as exit capacity. Turkey's Regulation on Fire Protection defines exit capacity as number of people that can pass in 50 cm in 1 minute and indicate exit capacities for different occupancies in Appendix 5/B [39]. In NFPA, capacity factors are given in Table 7.3.3.1 [37]. International Building Code shows exit capacities in section 1005 [38]. Exit capacity can be seen as an indicator that the time required for occupants to evacuate the building and it may be helpful to design exit widths of the building.

3.2. Vertical Egress Approaches

In accordance with the approach "In case of fire, use only stairs", some integrated strategies have been proposed and the general approach to this topic is evolving to the idea of "integrated strategies are more effective" [19].

3.2.1. Stairs

Stairs are generally considered most common egress component during emergencies. But evacuation by stairs is different than flat areas [40]. Although buildings with low number of floors are easier to descent to reach exits, it may be tiring to evacuate high-rise buildings via stairs. This is called fatigue effect and it can be said that fatigue effect needs to be researched deeper [2].
Designers must consider occupant load during design stage of the building to avoid congestion. Number of stairs, stair widths and location of stairs must be decided in accordance with occupant load. Locating floor exits on the opposite side of the incoming stair reduces the merging effect which will improve the evacuation efficiency [41]. Merging effect on stairs is reviewed deeper in Section 3.3.

3.2.2. Elevator Use

The idea of making elevators available to use during evacuation comes from early 1980's [30]. Advantages of the use of elevators during evacuation process can be listed as; moving faster than smoke, ease of evacuation for old, sick, disabled and the habit of using elevator during normal life [35]. Researches on effective use of elevator for evacuation purpose show that it is more effective to evacuate higher floors than lower floors [42,43]. Assuming that the fire will affect the elevator components, Hassanain indicated that on the upper floors of the fire, elevator shouldn't be used [1].
According to Proulx, the use of elevators during evacuation must be allowed [28]. There are a lot of successful evacuation by elevators [44]. In World Trade Center 2 (South Tower), the use of elevators during evacuation after WTC 1 was hit, made it available to save thousands of people's life [45]. Therefore, IBC recently allowed evacuation via preserved elevators [46]. This situation reflected to some countries' regulations as can be seen in Table 3.2. For example, evacuation elevators are compulsory for buildings higher than 24 m. in Singapore [47] and, fire elevator is compulsory for residential buildings higher than 32 m. in China [48]. Despite this, some countries do not allow elevator use for evacuation purpose. For example, Hong Kong Code of Practice on Building Works for Elevators and Escalators does not allow use of elevators for evacuation [33]. In Japan, emergency elevator is regulated in accordance with the height of the building [49]. Building Decree of Netherland permits fire department elevators to evacuate occupants and to carry fire fighters on condition that the elevator is designed against fire conditions [50]. Turkey's Regulation on Fire Protection does not consider elevator as an escape component but mandates at least 1 emergency elevator for buildings higher than 51.50 m. [39].

Table 3.2. Elevator Use for Evacuation Purpose in Codes and Standards

Code/Standard	Elevator Use for Evacuation Purpose
International Building Code [38]	Allow (Section 3008)
Code of Practice for Fire Precautions in Buildings (Singapore) [47]	Compulsory for buildings higher than 24 m.
Code for Fire Protection Design of Buildings (China) [48]	Fire elevator is compulsory for residential buildings higher than 32 m.
Code of Practice on Building Works for Elevators and Escalators (Hong Kong) [33]	Does not allow
Japan [49]	Regulated in accordance with the height of the building
Building Decree of Netherland [50]	Permits fire department elevators
Turkey's Regulation on Fire Protection [39]	Lifts are not accepted as an escape route At least 1 emergency elevator is compulsory for buildings higher than 51.50 m.

3.2.3. Refuge Floors

Refuge floors defined as floors that are isolated the effects of smoke and fire with at least 2 rooms separated by smokeproof components [37]. The occupants (especially sick, old and disabled) are expected to go to refuge floors and wait to be rescued. After 9/11 incident, the idea of waiting to be rescued in refuge floors has changed [33] because the building (WTC2) was collapsed less than one hour which was not enough to rescue occupants may be in the refuge floors. But there is a wide consensus for disabled, sick, pregnant and old occupants should use refuge floors to be safely rescued [51]. Some countries obligated the refuge floor for high-rise buildings. For example, according to Chinese Building Regulation, buildings higher than 100 m. must have refuge floor [42] and every refuge floor should service 15 floors max. [51]. Turkey's Regulation on Fire Protection has no standard about refuge floors. There are just standards about compartmenting in article 24 [39].

3.3. Merging Effect

Merging effect is observed on stairs where floor exits are connected. As can be seen in Figure 3.1, occupants descending from upper floors (painted blue) and occupants from current floor (painted red) are merging at the floor exit. According to researches, occupants coming from upstairs generally do not want to let occupants from current floor to get in the stair [30]. Peacock et al. indicated the 3 different merging behavior on high-rise buildings; occupants coming from upper floors may override occupants entering the stair, occupants entering the stair may override occupants coming from upper floors and finally neither of them may override and they split evenly [52]. Merging effect is observed more on floors that have more occupants and local speed is higher after these floors [14]. Because of the stagnancy at floor exit, there is more room to move which lead occupants to move faster for a while. Ronchi and Nilsson indicated that floors should be linked to stairs on the opposite side of the incoming stairs to lighten the merging effect [41]. According to experimental studies, merge ratio should be 50: 50 [11].

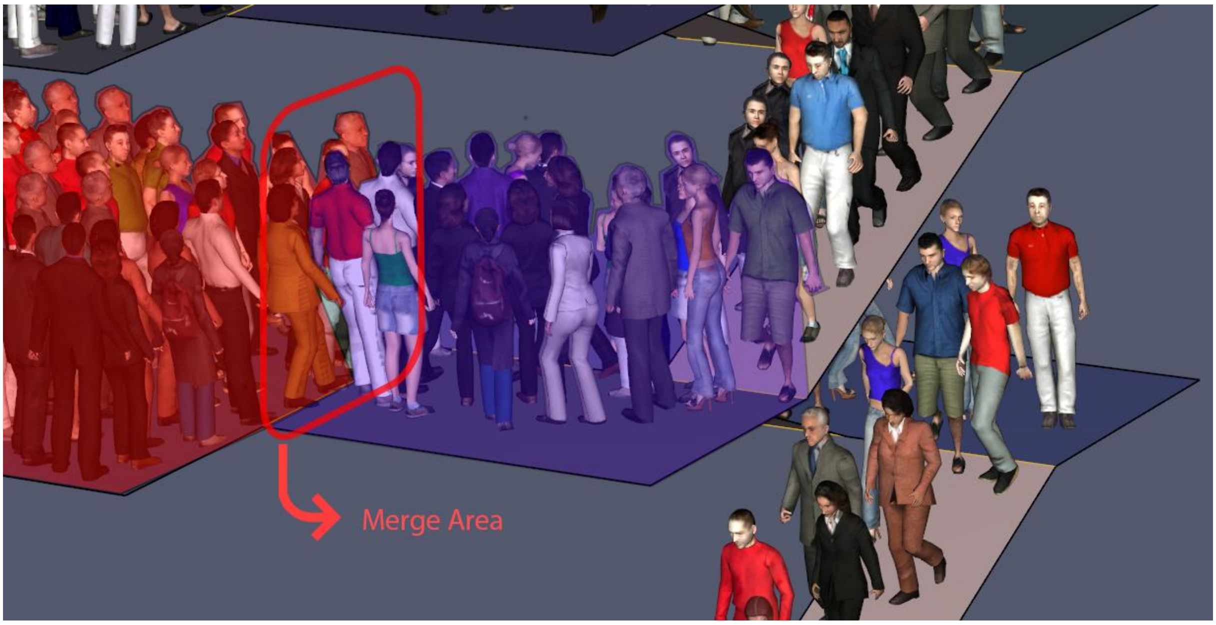

Figure 3.1. Merging Effect on Stairs

4. CODES and REGULATIONS on EVACUATION of HIGH-RISE BUILDINGS

Building regulations and codes on high-rise buildings are generally separated from low-rise buildings. This is because these buildings need different requirements than low-rise buildings. Some of these requirements are specific egress requirements, structural requirements and reachable height of fire trucks.

The definition of high-rise building varies from different codes and standards as it can be seen in Table 4.1. For example, NFPA 101 Life Safety Code and International Code Council define high-rise buildings as buildings with highest occupied floor higher than 23m. (75 ft.) [1,37]. Residential buildings higher than 27 m. and non-residential buildings higher than 24 m. are considered as high-rise buildings in China [48]. According to Hong Kong regulations, buildings higher than 30 m. are considered as high-rise buildings [29]. Building Decree of Netherland defines high-rise buildings as buildings higher than 70m. [50]. In Turkey, 21.50 m. is the lower limit of high-rise buildings [39].

Table 4.1. Definition of High-rise Building in Some Codes and Standards

Code/Standard	Definition of High-rise Building
NFPA 101 Life Safety Code [37]	23 m. (75ft.) or higher
International Code Council [38]	
Code for Fire Protection Design of Buildings (China) [48]	27 m. or higher for residential buildings 24 m. or higher for non-residential buildings
Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment, Fire Services Department (Hong Kong) [29]	30 m. or higher
Building Decree of Netherland [50]	70 m. or higher
Turkey's Regulation on Fire Protection [39]	21.50 m. or higher (7 floors or more)

5. DISCUSSION and CONCLUSION

In this article, the main approaches to evacuation of high-rise buildings are evaluated. Design parameters of high-rise buildings in terms of evacuation are reviewed, analyzed and classified. Main findings can be summarized as in Table 5.1.

Table 5.1. Identified Key Points on Evacuation of High-rise Buildings

•High-rise buildings are harder to handle in terms of evacuation since they require complex solutions.
•The topic is important for Turkey since Istanbul is the 4th city with most skyscrapers.
•Evacuation timeline has a crucial role on safe evacuation.
•Pre-evacuation time is the most uncertain part and each country should prepare their own database.
•Egress strategy of the building must be decided during the planning stage.
•Occupant load and exit capacity must be considered during the planning stage.
•Human behavior in emergency evacuations has a lot of blind spots and need deeper research.
•Although descending a high-rise building via stairs is difficult, enough stairs to evacuate the building by only stairs must be planned.
•Elevator use in purpose of evacuation is a controversial topic and need deeper research.
•There are no standards on refuge floors in Turkey.
•Merging effect must be considered during the planning stage.

It is seen that evacuation approach to high-rise buildings has differences from low-rise buildings. High number of occupants and long egress routes are some of the elements that challenge the evacuation of high-rise buildings. Being Istanbul is the 4th city with the most skyscrapers in the world, reveals the importance of the topic for Turkey. When the literature is reviewed, there is just a few researches in Turkey on evacuation of high-rise buildings [3,53]. This article purposed to review the point reached on evacuation of high-rise buildings for Turkey.

It is observed that especially human behavior during emergencies needs to be researched deeper. Although there are numerous researches about human behavior, there is still lack of information about the topic. Considering human behavior during emergency conditions vary between different nationalities, the behavior of Turkish people needs to be clarified. Researches on human behavior for Turkish people will be a guide to clarify pre-evacuation times for different occupant types in Turkey.

Architectural design of the building has a crucial role to provide a safe evacuation for occupants. Egress components must be designed in accordance with occupant load and exit capacity. Location and width of stairs has a vital effect to prevent congestions. Also, uneven distribution of occupants to the stairs may lead inefficient use of stairs and may cause delays.

When the researches, codes, regulations are reviewed for high-rise buildings it is observed that the disagreements and conflicts are gathered around the use of elevator for evacuation purpose. Although some codes mandate emergency elevators, some codes do not allow the use of elevators during evacuations. Being there are different approaches to this topic indicate that future researches need to be concentrated around this topic.

CONFLICT of INTEREST

No conflict of interest was declared by the authors.

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