YANGIN KOŞULLARI ALTINDAKI YÜKSEK KATLI KONUTLARDA TAHLİYE

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ÖZET: Yapılarda yaşayanların güvenliğini sağlamak için yangın yönetmelikleri genellikle tasarımda karşılanması gereken minimum gereksinimleri belirtir. Sayısı gittikçe artan yüksek katlı konutlar ile olası bir yangından kaynaklanacak riskler artmıştır. Bu çalışmada yüksek katlı konutlarda, ileri seviye nümerik yöntemlerle yangın ve duman dağılımının etkisini de hesaba katarak tahliye analizi yapılmıştır. Sonuçlar, bu tür yüksek binalarda tahliye zamanının yangının çıktığı kata göre ciddi farklılık göstermesi ve tahliye davranışının 4-5 katlı konut binalarından çok farklı olduğunu göstermektedir. Bu çalışma ile yangın mühendisliğinin bir parçası olan tahliye senaryolarının daha doğru şekilde üretilmesi ve bina tasarımının bu senaryolara göre yapılması amaçlanmıştır.

Anahtar kelimeler: tahliye, yüksek binalar, yüksek katlı konutlar, yangın mühendisliği

Egress in Tall Residential Buildings under Fire Conditions

ABSTRACT: In order to ensure the life safety of residents, building codes often establish the minimum requirements to be met in fire safety design. On the other hand, the increasing number of complex modern high-rise residential buildings suggests an increased risk of major consequences resulting from fire hazards. This indicates that the ability to mitigate the threats posed by fire to high-rise building residents should be of primary concern and surpass the minimum safety criteria. In view of the challenges faced when modelling egress in tall residential buildings, the current understanding of fire and evacuation has been synthesized to propose a robust framework for evaluating the life safety of occupants in tall residential buildings. The results demonstrate how the egress behavior of such buildings differ from that of conventional low-rise buildings as well as the importance of characterizing the different levels of risk incurred by different occupants due to fire outbreak on different floors. This is intended to provide additional guidance to building designers and researchers in the field of performance-based fire safety.

Keywords: egress, high rise, tall buildings, evacuation, fire engineering

1. INTRODUCTION

One of the most important issues in the design of high-rise buildings is ensuring that in the case of an emergency situation such as the event of an earthquake or fire its occupants are able to safely evacuate before the conditions within the building become untenable. Over the past decades, cities all around the world have experienced a steady influx of migrants thus increasing their need for more residential buildings. Istanbul is among the cities with the highest number of skyscrapers in Europe and given the current continual growth of urban population and the limited land resource, high-rise residential buildings will only continue to increase in number in these growing cities.

Evacuation of people can prove to be a complex task, and with high-rise buildings this issue is even more paramount. Several procedures can be taken in design and construction that will decrease the likelihood of a fire outbreak. Nevertheless, even if rare in occurrence, the event of fire in tall residential buildings can have devastating consequences as several incidents in history have demonstrated. The MGM grand fire which occurred in Nevada in 1980, for example, is said to have killed at least 87 people and injured 650 others (Dailymail, 2012). In 1974, Joelma Building fire in Brazil left 179 people dead, injuring another 300 (Craighead, 2009). Also, as in the case of Meridian Plaza fire in Philadelphia, without adequate consideration of evacuation for an emergency, even the fire-fighters themselves could be among the casualties. With almost 3,000 deaths and 6,000 injuries, the World Trade Centre terrorist attack has shown the importance of ensuring safe evacuation of occupants during an emergency situation (Ronchi and Nilsson, 2013). Since then, more robust strategies for the evacuation of people in high-rise buildings have been sought including several combinations of total evacuation strategies (Ronchi and Nilsson, 2014). More recently, Grenfell fire which killed 72 people has questioned the appropriateness of alternative evacuation strategies such as defend-in-place strategy thus demonstrating the significance of planning for the evacuation of entire occupants (Hopkin, et. al., 2019).

Research on previous fire deaths and injuries has demonstrated the potential for saving more occupants who have died from fire (Hall, 2004). To provide an accurate representation of potential fire scenarios, several factors need to be taken into account not least the social and fire culture of the particular occupants (Özkaya, 2001). Although the majority of published data used in fire engineering application comes from a small number of countries with broadly similar backgrounds (Galea *et. al.*, 2015), the need for justifiable use and extrapolations of the available data has prompted efforts to establish a database for evacuation parameters (Lovreglio *et. al.*, 2016; Shi et. al., 2008). Factors contributing to egress performance relate primarily to the characteristic features of the building (Galea, *et. al.,* 2008; Ma *et. al.*, 2012) and the behavior of the evacuees (Ma *et. al.*, 2012). Occupants' exposure to the effluents produced by fire in a burning building can exact influence on this movement behavior and choice of exit route (Bryan, 2002). The choice of exit determines the travel path and hence the distance and speed of evacuation. In residential buildings, occupants are usually expected to use exits with which they are familiar, and that is largely restricted by the building's architectural plan. The standard requirements for the building geometry are usually regulated by the codes and standards applicable in the respective countries. Other requirements concerning the expected features of the occupants are also stipulated in these and several other guidelines.

2. REVIEW OF CURRENT REGULATIONS AND GUIDELINES

According to NFPA 101, buildings above 23m are considered to be high-rise buildings. The prescriptive codes currently in use have evolved from previously adopted design philosophies. The US codes, for example, design exits for capacity so that all the occupants on each floor can be stored on the stairs allowing for orderly evacuation. This led to the adoption of the 44 in. (112cm) stair width in new buildings as this was said to be "sufficient to prevent three persons from forming an arch and blocking traffic" (Bukowski, 2009). Other regulations are also based on similar or same principles and egress systems are generally designed to protect occupants who are not intimate with the initial fire.

In the Turkish fire code, an occupant flow rate of 40 people/min from a width of 50cm is adopted (Oven and Cakaci, 2008). The minimum width for the corridors and stairs is 120 cm, and two stairway exits must be provided for high-rise buildings. Lifts are only used for fire-fighting purposes and occupants are therefore expected to use the traditional means of escape, i.e. stairs for fire escape. Some codes, however, do allow for the use of elevators which has been found to improve the efficiency of the evacuation (Kuligowski, 2003; Ronchi and Nilsson, 2013).

The number of occupants in the building is also a major factor in determining the evacuation time and consequently the risk posed on people in the event of fire. NFPA 101 specifies an occupant load factor of 18.6 m^2/person based on a slightly reduced total area known as the 'gross leasable area' while BYKHY proposes a user load factor of 20 m^2/person for residential apartments which is also in line with several other jurisdictions. These values are in general used to calculate the occupant density from which the total number of occupants in a building during fire evacuation can be simulated and are based on either the floor area or the number bedrooms. Using the high-rise residential building data in Istanbul, a typical size and height has been chosen to perform a generic analysis of the egress behavior during fire in such buildings.

3. EGRESS AND FIRE

From a point of view of life safety, two parallel aspects are considered during fire evacuation analysis. These are the Allowable Safe Egress Time, ASET, which is an outcome of fire, and Required Safe Egress Time, RSET, the outcome of evacuation. As the performance-based approach has taken hold in the design process for reducing risk to an appropriate level, both of these quantities need to be with determined with a reasonable amount of accuracy. The situation of a building under fire necessitating an urgent evacuation of its occupants is triggered by an accidental or deliberate kindling of a flammable substance. In the case where this process has proceeded for longer than can be extinguished easily, passive protection systems can only slow down the ASET for the occupants to evacuate. The installation of active fire protection systems such as sprinklers, although effective, can also not be relied upon to provide full protection to the lives of the occupants (Oven and Cakaci, 2008). To restrain the potential detriment of the growing fire on occupants, the flashover period is one of the most important factors in ASET estimation.

Developments in technology and computing power has allowed for the feasibility of applying the known fundamental equations of fluid dynamics, heat transfer and combustion to model the evolution of fire with high degree of accuracy. Models of varying sophistication have emerged each relying upon a fixed set of assumptions and physical and chemical principles that can be used to predict pre-flashover fires. Among them is Computational Fluid Dynamics or CFD model, a highly sophisticated technique that numerically solves a time-averaged or space-averaged form of the conservation equations. Fire simulation tools based on this model allow for a convenient application of data or scenario configuration to simulate the effects of fire including radiation (Wang *et. al.*, 2005).

The likelihood of fire initiation in a high-rise building is greater on the lower floors, thus putting a greater number of occupants at risk. In fact, most of the fires in the past have begun on the 6th floor or below (Hall, 2013). Also, furnishings common in residential buildings have low thermal inertia which implies a rapid burning and flame spread. Such fires in which these items are the first to ignite are said to be the leading cause of death (Blais *et. al.*, 2019). Radiation plays an additional role in the burning rate especially in small compartments or those with large openings (Peacock *et. al.*, 1999). Due to the nonuniform fire distribution in rooms, the temperature along the doorway is sometimes used as the defining temperature for flashover (Peacock *et. al.*, 1999). The distribution of smoke and fire effluents are equally important when it comes to the life safety of the occupants. As we shall see, in high-rise buildings, the location of the fire along the height of the building is key in determining the number of people of who are most at risk due to the fire hazard.

3.1 Egress Modeling

The study of human egress from building fires first began with a focus primarily on the movement of people within the egress components (Kobes *et. al.*, 2009). This served as the determining factor for safety and the design of stairs was carried out so that sufficient capacity is provided to accommodate the simultaneous evacuation of the entire building or of certain floors. This approach led to the prescriptions of minimum widths for stairs, corridors and other egress components (Pauls *et. al.,* 2005) and the prescriptive codes that resulted from such an approach are now based on flow rates, travel distance, exit numbers and exit widths. Later, recognizing the impact of how a building is used affects the egress performance, emphasis shifted to the behavioral aspect of the evacuation. Theories on human behavior during emergency situations still continues to be refined and adopted with our prevailing understanding to more accurately represent hypothetical evacuation scenarios. A comprehensive conceptual model, however, is still an ongoing research area (Gwynne *et. al.*, 2015). In general, behaviors during two broad phases of evacuation can be observed (Purser and Bensilum, 2001). These phases are pre-evacuation phase and evacuation movement phase. For different building uses, the differences in the characteristics of the occupants and of the building make the nature of evacuation different. Occupants in residential buildings exhibit higher pre-evacuation times than in other building types due to the fact that occupants in these buildings are often less prepared for evacuation or may even be reluctant to move out than those in other building types (Ronchi and Nilsson, 2013). The pre-evacuation phase is further divided into two distinct phases: recognition phase, the time from the first cue or alarm to the time when the decision to evacuate is made, and response phase, the time from when the decision is made to the time when evacuation movement begins. The interaction between many egress variables have been shown to require more than these deterministic rules in order to properly determine the evacuation time as well as the general egress performance (Oven and Cakaci, 2008).

In modelling the pre-evacuation times of occupants, pre-defined evacuation times or a series of itinerary list can be assigned to each occupant. An alternative is to apply an evacuation decision model with predictive capabilities based on internal and external factors, although this is rarely implemented in current computer models (Lovreglio *et. al.*, 2016). The type of alarm system also influences the pre-evacuation time (Shi *et. al.*, 2008). Several activities, cognitive and physical, occur during the response phase and the fire culture, namely alarm system, and the social culture, are some of the main determinants of the response phase behaviors (Galea *et. al.*, 2015). According to the framework used for decision making known as the Protective Action Decision Model (PADM) (Lindell and Perry, 2012), occupants act on information they receive, and this is used to describe the response phase behavior. The pre-evacuation time distribution of occupants generally follows a log-normal distribution (Forssberg, *et. al.*, 2019; Galea *et. al.*, 2015; Purser and Bensilum, 2001). Research has also been carried out to identify the characteristics of people and their circumstance that influence the length of pre-evacuation time during evacuation. A correlation has been found between occupant's vertical position in the building and pre-evacuation delay (Kuligowski and Dennis, 2009). Occupants on lower floors display higher pre-evacuation times than those above. An evacuation that involves people on higher floors reaching the stairs before those on the lower floors will result in queues forming on the stairs as the occupants are being discharged out of the building.

In the second half of the last century, hydraulic models were applied to study the physical movement of people in buildings (Pauls, 1987). According to this model, the speed with which occupants are able to move through the egress components is largely a function of the population density. One major drawback of this fluid model is lack of intrinsic capability to account for congestions. Advanced computer models are able to represent these complex interactions between evacuees with their environment and with other evacuees (Gwynne *et. al.*, 1999: (Ronchi and Nilsson, 2013). The early computer models created to simulate the evacuation problem evaluated the delays resulting from queuing during movement did not represent the location of the queuing (Oven and Cakaci, 2008). Transit from one egress component to the other results in additional evacuation time (Ma *et. al.*, 2012) and for tall building evacuation, research also show a decrease in the average speed of evacuees during the process (Ma *et. al.*, 2012) (McConnell *et. al.,* 2009). Using an agent-based model developed later, the flow of the occupants and their merging process at points of contact can be investigated (Galea, *et. al.* 2008). With this model, evacuees respond spontaneously to their environment within realistic boundaries.

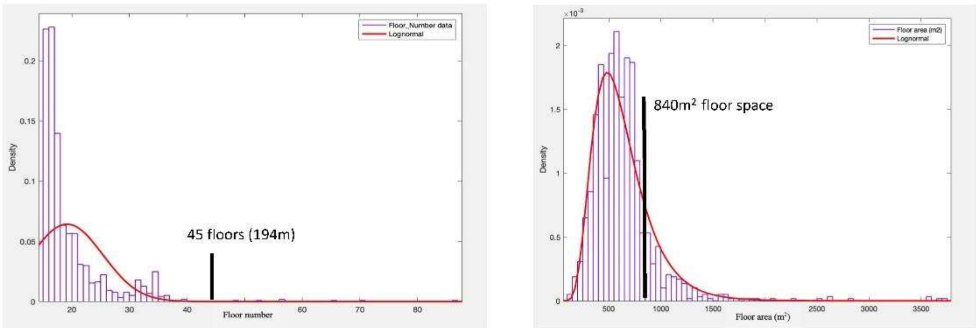
3.2 Interaction between fire and human behavior

As mentioned before, human behavior is one of the key aspects of evacuation considered in egress modelling. In the context of evacuation from a building in fire, these behaviors are influenced by the changing environmental characteristics induced by the fire which include heat, irritants, and other fire hazards. Crucial in the utility of fire models is the spatial and temporal prediction of temperature and smoke. In a tall residential building where the evacuation is more vertical than horizontal, occupants coming down make longer contact with smoke and other toxic gases especially for a fire occurring on the lower floors (Oven and Cakaci, 2008). The toxic gases known to influence human behavior during the evacuation include HCN, CO, CO_2, and the depletion of oxygen (Oven and Cakaci, 2008). The effects of these and the temperature and smoke concentrations on evacuation have been investigated using the hypothetical values shown in Table 1. Smoke produced impair visibility of occupants thereby affecting the occupants' choice of exit and irritant gases also exacerbate the effects of smoke (SFPE Task Group, 2019).

As the evacuees come into contact with these fire effluents, their mobility is impaired. Additionally, since all occupants experience different levels of toxicity and have different tolerance levels, the degree of influence varies across the population. This makes the use of a computer simulation tool with an algorithm designed to be able to perceive such differences useful. In the case study described in this paper, the Turkish demographic has been used to construct the simulation model in the EXODUS evacuation model (Galea *et. al.*, 2015; Oven and Cakaci, 2008). The occupant characteristics that guide the simulation include agility when an obstacle is encountered, drive or assertiveness used to resolve conflict between two or more evacuees meeting at a particular point. These and other characteristics can be grouped into physical and psychological attributes of the evacuees. During the simulation, other attributes such as the total time spent in queues also emerge as experiential attributes. A pure egress phenomenon or an interactive people-fire evacuation with heat and narcotic gases taken into account can also be considered. In the present analyses, both have been considered.

4. CASE STUDY

Three age groups have been chosen to represent the population demographic. A roughly equal male to female ratio is distributed among the groups: 40% aged 12-29 years, 40% aged 30-50 years and 20% aged 50-80 years. The agility, drive, and patience times of males and females are randomly distributed with females having slightly higher values than males but with a significant overlap. Since the location of each occupant cannot be known with certainty, the occupants are also randomly located on each floor. This is consistent with the proportion of the amount of time it takes occupants on each floor to reach the stairs versus the time it takes to evacuate the stairs entirely. For the fire scenario as well, the distribution of the fire has been taken to be even throughout the floor it occurred and for the whole height since the effect of fire occurring on the specific floor of the tall building is the variable under investigation. As Figure 1 indicates, the area distribution of high-rise buildings in Istanbul falls on a log-normal distribution function. The floor number of the buildings is also represented by a log-normal distribution. To represent a typical tall residential building in Turkey, the mean value has been utilized for the area and the 99th percentile for the height of tall residential buildings. The tall building selected for the case study is 45 floors above ground with $840m^2$ floor area. Figure 2 shows the floor layout of the high-rise building under investigation. Each floor has 4 apartments with two exit stairways. There are 43 occupants on each floor with 6th and 29th floors unoccupied as they are utilized for mechanical equipment, which makes a total of 1849 evacuees. The architectural plan also conforms to the Turkish Fire Safety Code.



(a) (b)

Figure 1. Probability Density Function of Istanbul High-rise (a) Building Height – Number of Floors and (b) Floor Area (m^2)

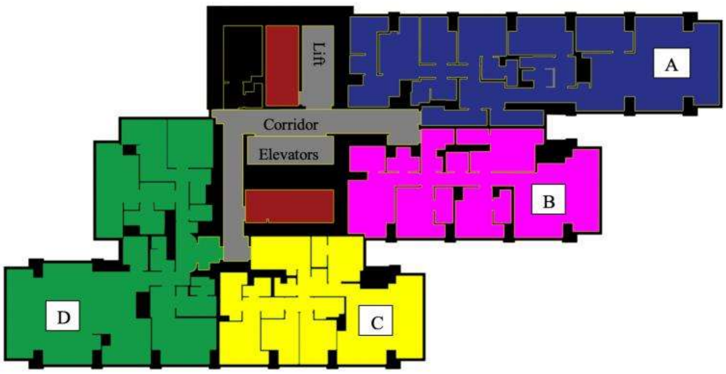
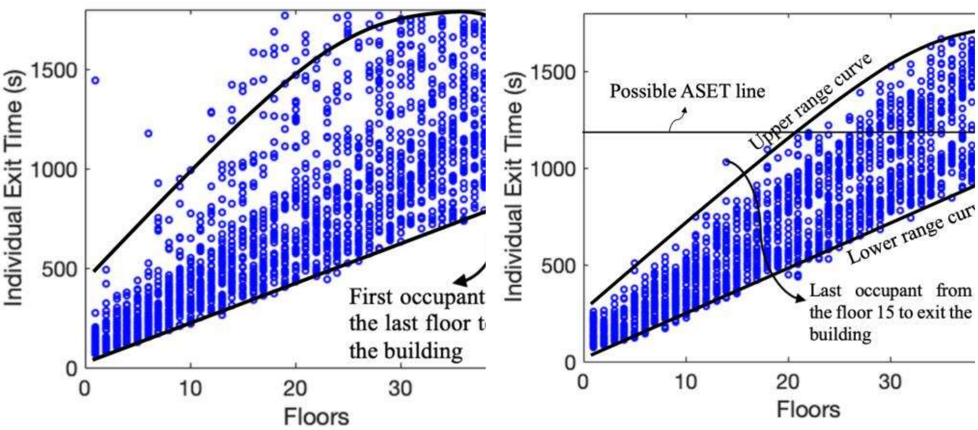


Figure 2. Floor Layout of the Tall Residential Building Case Study

The simulated results of evacuation in the building without considering the influence of fire and one in which fire and smoke influence are considered have been programmed into an assembly code that generates the exit time for each particular occupant from the top to the bottom floor. Figure 3a shows the exit time graph of the realistic scenario (Scenario A in Table 1) outlined in the previous paragraph. Each bubble on the graph represents an occupant starting evacuation from a particular floor and the time elapsed at the point of exit out of the building is given by the y-axis. The area between the upper and lower curves in Figure 3 designate the time range that occupants spent on each floor (i.e. time difference between first and last person leaving each floor). As seen, occupants spend more time on upper floors due to queuing on stairways. To investigate another scenario (Scenario B in Table 1) in which all the attributes of the entire occupants except the starting location are exactly identical, a different graph is produced given by Figure 3b. Here, the time range on each floor gets smaller since every occupant has the same response and move in unison.



(a) (b)

Figure 3. Egress of (a) Scenario A - randomly diverse behaved occupants and (b) Scenario B -homogeneously behaved occupants in a typical tall residential building without fire influence.

The contrast between Figure 3a and Figure 3b demonstrates the difference of having a realistic representation of the diversity of a set of occupants in a tall residential building. Although the total evacuation time does not differ by much in this case, the time spent on each floor shows a significant variation. This is particularly consequential in the case of a fire on a lower floor especially one that is growing fast or had gone undetected for long before the evacuation began. For example, if the flashover time is said to be 1200 seconds, the number of occupants trapped will be greater in Figure 3a than it would have been if Figure 3b scenario is considered.

Table 1. Egress scenarios.

Egress Scenarios	Fire	Fire Floor	Number of occupants	Total Egress Time	Number of Casualties
Scenario A	no	-	1849	1766 secs	-
Scenario B	no	-	1849	1682 secs	-
Scenario C	yes	29^{th}	1849	1143 secs	640
Scenario D	yes	6^{th}	1849	1562 secs	1044

Another important point to observe is that evacuation from each floor begins before the occupants on the preceding floors are fully evacuated. Also, the rate of increase in time for first occupant evacuation from each floor is roughly linear. This implies that on each floor, after the occupants move horizontally to the stairs, the flow down the stairs within the queue formed, i.e. the entrance into the queue, is roughly the same. As with the hydraulic model, the queuing starts at the junction between the stairs and the corridors on each floor. On the other hand, the last occupant to evacuate from each floor varies nonlinearly owing to the change in density and conditions of the egress with time. Moreover, Figure 3a indicates that some amount of time is spent during conflict resolution which makes the Figure sparser. It might even be the case that an occupant remains stuck in a queue for an inordinately long time relative to their floor companions as the outlier on the first floor demonstrates.

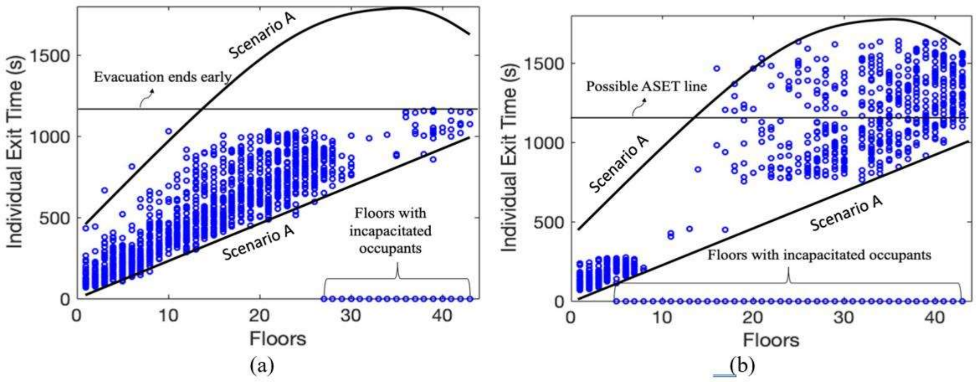
Table 2. Assumed toxicity concentrations of temperature, heat and asphyxiants.

	Temp	Smoke	HCN	CO
Value at t = 0	20˚C	0	0	0
Value at t = 1000s	120˚C	43.5 OD/m	100 ppm	100 ppm
Value at t = 2000s	220˚C	87 OD/m	200 ppm	200 ppm

To investigate the effect of toxic gases on egress, simplified linear fire growth assumptions have been made regarding CO, CO_2, HCN and temperature whilst the fire scenario was created. Table 1 shows the values at three particular time periods. Two fire locations are investigated, one of which fire is assumed to occur on the mechanical floor, where there was initially no occupant load. For Scenario C in Table 1, fire spreads from 29th floor space to the stairways. HCN and CO toxic gases are measured in particles per million (ppm) and smoke density is measured in optical density per meter (OD/m). As Figure 4a shows, with a null exit time of for occupants that have collapsed and are incapacitated (i.e. causalities), it can be observed that all of them are above floor 25. Interestingly, no occupant from floor 31 survives and occupants closest to the fire floor are the most affected. From the total of 1849 building occupants, fire on 29th floor has resulted in 35% casualties.

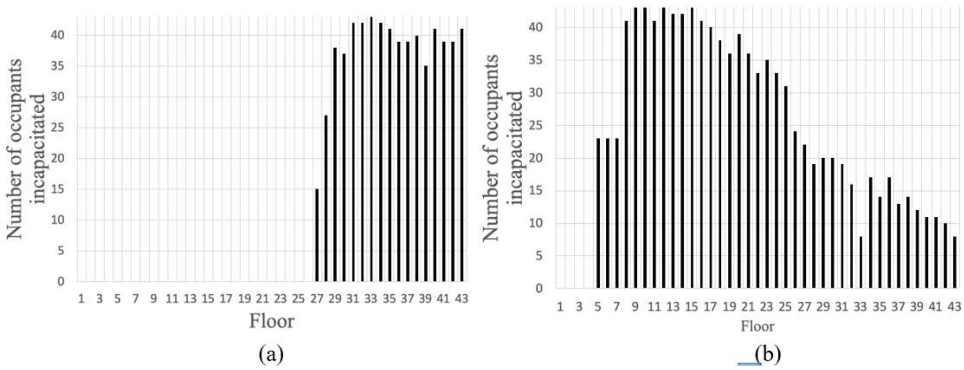
In Scenario D, the fire occurs on the 6th floor. As shown in Figure 4b, the number of causalities has jumped from 35% to 56%. For this scenario, the floor closest to the fire location experienced the maximum number of casualties as well. On some of the floors all the occupants are incapacitated before reaching safety. In addition to more casualties, the building evacuation took 25% longer for this scenario. This result indicates that occupants who slow down due to fire and smoke effects have also contributed significantly to the evacuation delay and queueing.

Fire effects in Scenario C can be compared with the egress scenario without a fire event (Scenario A). The total evacuation time has decreased by 35%. Occupants below fire location move with the same pace as in Egress Scenario A while some of those on floors above have been incapacitated during the process, and since they are the last to evacuate in any scenario, hence the shorter total evacuation time. For Scenario D, fire on 6th floor means that more occupants will be subjected to fire effluents, hence the casualties are found almost on each floor above the 6th floor. Their contribution to the queuing effect is preserved even though they do not make it out of the building. In other words, the major cause of their death may have been the toxicity of fire rather than insufficient evacuation time. The upper and lower range curves extrapolated from Scenarios A are superimposed on Figure 4a and Figure 4b. It is clearly observed that fire on upper floors leads to an overall shorter total evacuation time with casualties coming mostly from the upper floors while fire on lower floors leads to casualties on the floors mostly closer to the fire location but almost on each floor. Scenario D has an overall similar evacuation time compared with egress without fire event (Scenario A). This nugatory involvement in the evacuation has not aided those not intimate with fire to evacuate earlier. Rather, the overall shape of the egress range remained unchanged while the futile attempt of the incapacitated occupants remained inconsequential on the total evacuation time with substantial loss of lives. Figure 5 shows the distribution of the casualties for both Scenario C and Scenario D.



(a) (b)

Figure 4. Egress in high-rise residential building (a) Scenario C – fire on 29th floor and (b) Scenario D – fire on 6th floor.



(a) (b)

Figure 5. Distribution of incapacitated occupants for (a) Scenario C and (b) Scenario D.

5. CONCLUSION

This paper has explicated the concept of egress in a high-rise residential building and the present development in this research area. The influence of fire on evacuating occupants has been integrated into the egress analysis to produce a more realistic scenario of evacuation from the high-rise building during fire. The effects of fire and fire location to the evacuation time and casualties have shown to be significant. Main conclusions are as in the following:

- For high-rise evacuation, time spent on each floor varies considerably, generally it increases non-linearly towards upper floors. This indicates larger RSET for upper floors, hence larger ASET is required for upper floors.
- The diversity of agility, drive and speed of occupants does not change the total evacuation time but it increases the average time spent on each floor.
- Fire floor creates casualties mostly on above and some on below floors but the affect is limited to several floors due to dilution of smoke and toxic gas effects. Occupants on upper floors are incapacitated as they pass stairs in fire floor range.
- Fire location changes the egress time as well as number of casualties considerably. Fire on lower floors increases casualties as well as egress time due to queuing effect of slowed down occupants on fire location to the occupants above.

There are complex interactive occupant variables with specific or joint effects on egress performance. The evacuation itself is a stochastic process and these variables should be treated as such in order to more appropriately describe this phenomenon. The occupant load derived from regulations, for example, vary from one code to another (Spearpoint and Hopkin, 2019). In another study, the historical sources of the deterministic occupant load values in other types of buildings have been questioned especially for use in a probabilistic study of the risk of fire to occupants (Hopkin *et. al.*, 2019).

For a city-wide risk assessment, more complex higher-order models considering other unique features of a tall residential buildings should be used to ensure the safety of tall buildings occupants. This represents an important step towards unraveling the best ways to improve life safety in high-rise buildings, which can be applied to further study the issue. Occupants need to be protected from fire because they are at risk of death if not by being trapped in a blazing building then of asphyxiation due to the effects resulted from the fire.

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