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Egress Parameters Influencing Emergency Evacuation in High-Rise Buildings

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Abstract. Fire in buildings pose a significant threat to occupants, first responders as well as the structural system. Rapid spread of fire and smoke in buildings can hinder the process of evacuation resulting in loss of human life. Such situations call for a reliable egress system that provides safe evacuation of occupants in minimal time. Updating the occupants and first responders with much-needed situational awareness such as accessible stairwells and exits during the disaster can not only lead to efficient evacuation but also shorten the duration of evacuation in some scenarios. This paper examines occupant evacuation scenarios in fire exposed high-rise buildings. A parametric study is carried out on evacuation strategies in a 32-story typical office building during different fire exposure scenarios. The movement of occupants with and without situational awareness is simulated. The effect of critical parameters such as number of stories, width of the egress paths, location and number of exits on the evacuation process is evaluated. The time required for occupants to evacuate the building is estimated under normal conditions (to simulate fire evacuation drill) and under realistic fire exposure. Results from the study indicate that the two most significant factors that influence evacuation time are the location of stairway within the building and the floors at which fire starts. When fire starts at the lower levels of the building, the evacuation time is the highest. More importantly, if situational awareness is incorporated in emergency evacuation procedure, it can improve the evacuation efficiency in a fire exposed high-rise building; wherein up to 24% reduction in evacuation time is achieved.

Keywords: Evacuation, Emergency, Fire, Stairway geometry, Egress strategies, Situational awareness

1. Introduction

High-rise buildings can be subjected to natural or manmade hazards during their service life which may necessitate emergency evacuation [1, 2]. Efficient evacuation of occupants in a high-rise building is a growing concern especially in the event of an emergency situation such as fire in a building [3]. The latest statistics from the National Fire Protection Association (NFPA) report an average of 14,500 fires in high-rise buildings which resulted in 40 civilian deaths and 520 civilian injuries per

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year [4]. The high incidence of fire events indicated in this report undermines the role of evacuation in ensuring the safety of occupants of a building. The spread of fire, flames, toxic gases from combustion and smoke, may result in inaccessible exit routes, reduced visibility and congestion which in turn impede the process of evacuation [5]. Therefore, it becomes crucial to design a robust egress system which ensures safe and fast evacuation in the time of emergencies, as encountered during a fire incident.

The egress system in a high-rise building often comprises of one or more egress components such as stairways, refuge floors, sky bridges, etc. The geometric characteristics of the egress system such as width, number and arrangement of exit paths (stairs) determine the efficiency of the evacuation process. These factors are usually stipulated in the building codes such as the International Building Code (IBC 2018) [6] and are prescriptive in nature. The code provisions establish the minimum requirements for the design of egress system and often do not account for the complex issues that arise during emergency evacuation. Further, the behavior of humans during emergency situations also plays a critical role in building evacuation. Occupants tend to get involved in different activities, such as, locating the fire zone, trying to put off the fire, warning and searching for fellow occupants, etc. that cause delays in the evacuation process [5]. Speed and movement of occupants through the egress routes are affected by human factors such as age, gender, physical disabilities, behavioral patterns, etc. [5]. In emergency situations, such as fire in a building, way-finding (i.e. how the evacuees find their way to the exits) also affects the flow of occupants due to issues arising from possible blockage of exit routes on account of smoke, counterflow during firefighting operations, etc. [7]. A review on human behavior during fire incidents in buildings by Kobes et al. [8] showed that it is essential to take a holistic approach in modelling building evacuation by incorporating the characteristics of fire growth, human behavior, and building topology.

Different analytical and computer models have been used in the literature to model evacuation in high-rise buildings. The Society of Fire Protection Engineers (SFPE) Handbook [5] provides an analytical hydraulic model to estimate the evacuation time. It is an engineering method that uses a series of equations to represent the flow of occupants from one egress component to another. The change in flow of people at critical regions of transitions (such as door entrance or staircase entrance) is captured. The results obtained from the model are quantitative but only work for symmetric and simple building layouts. It is not efficient for calculating evacuation time for complex structures under real fire conditions. In addition, the model does not account for varying human behavior during evacuation.

Computer models allow for a more detailed evaluation of the evacuation process. The most recent review by Kuligowski et al. [9] provides a detailed characterization of 28 egress models. The models were compared based on the approach adopted to simulate evacuation, movement, behavioral capabilities and other features specific to each model. The review provides information for choosing suitable models for specific studies. Ronchi et al. [10] presented a list of tests for validation of building evacuation models. These tests were designed to evaluate different capabilities of the evacuation models such as pre-evacuation time, movement and navigation of occupants, exit usage, route availability and flow constraints. Ronchi and Nilsson [3] compared seven evacuation strategies in high-rise buildings using a combination of different egress components, such as stairs, elevators, transfer floors and sky-bridges. Strategies involving sole use of elevators and employing combined vertical (stairs and elevators) and horizontal (transfer floors and sky bridges) egress components were found to be most efficient. The study did not include the effect of fire scenarios and geometric characteristics of egress components on the evacuation process. Soltanzadeh et al. [11] evaluated the use of refuge floors in combination with other egress components (such as stairs and elevators) for evacuation. The study concluded that increasing the number the refuge floors in a building increased the evacuation time due to congestion. Providing a single refuge floor at mid-height was found to be optimum based on the study of a 40-story high building. The evacuation study, however, did not consider varying building heights and fire exposure scenarios.

In the event of an emergency, it is crucial to provide enough time for occupants and first responders to tackle the adverse effects of the disaster and safely evacuate the building. Prior research has shown that resilient structural systems that maintain acceptable levels of functionality during and after a disaster improves the efficiency of evacuation and response operations under emergencies [12–14]. In a recent study, Naser and Kodur [12] showed that incorporating cognitive abilities to a structure to enhance resilience can aid in the process of evacuation. A framework of integrating sensors with structural members to provide situational awareness during emergency evacuation was presented in this work. Situational awareness allows occupants and first responders to comprehend the severity of the disaster, such as location of people within the building and nature of fire growth. It also provides a future projection of the status of the building and occupants that can assist in the process of evacuation.

The building and egress system design typically follows the prescriptive approach in building codes. Past studies that consider geometric analysis of egress components are based on the traditional hydraulic model calculations that are simplistic and do not account for human interactions during evacuation. This paper examines the adequacy of the existing provisions for egress system design in high-rise buildings in facilitating emergency evacuation during a fire incident. Specific attention is given to incorporate recent changes made in the International Building Code (IBC 2018) [6] in terms of number and sizing of egress components in high-rise buildings. A parametric study of different evacuation scenarios is conducted to quantify the effect of story height, fire location and size, number and arrangement of exit paths. The evacuation simulations are carried out using the computer model Pathfinder [15], wherein, complex human behavior during evacuation such as collision avoidance and route choice are considered. Possible improvements and alternatives to the current code provisions are proposed to improve the evacuation efficiency during emergencies. In addition, the impact of introducing situational awareness during emergency evacuation is evaluated.

2. Factors Governing Fire Evacuation

Evacuation during a fire incident is usually complex and depends on several factors that can be grouped under one of the following categories, namely, geometry of the building, fire characteristics and human aspects [8]. Building geometry includes architectural layout, dimensions and shape of the structure, number and arrangement of egress paths, travel distances, separation between exits, etc. Gwynne et al. [16] inferred that the response of occupants during emergency evacuation directly depends on these factors, for example, preference to use certain exits, familiarity with the egress route and wayfinding during the process of evacuation. Factors such as passive protection (fire resistance) measures present in the building also comes under this category [5]. The construction materials used for the structural system and type of fire protection influences the fire resistance, and thus the time available for occupant evacuation and rescue operations.

Fire characteristics govern the nature of fire development and spread within the building. Figure 1 shows the different phases in the development of a typical compartment fire. The duration of each phase depends on factors such as geometry and physical dimensions of the compartment, fuel load, fuel type and ventilation [17]. Most of the evacuation should occur during the initial ignition phase when the temperatures in the compartment are low and there is very little or no toxic gases. According to NIST [18], when the human skin temperature reaches 72°C, either from direct contact with fire/smoke or through convection and radiation, the skin is completely burnt (destroyed). Beyond this stage, evacuation becomes difficult. The level of active fire protection (such as sprinklers, extinguishers, etc.) and compartmentation restrict the amount of fire spread that can occur within a building. In the survey conducted by NFPA [4], office buildings have the highest probability for fire spread beyond the room and floor of origin. Fire and resulting smoke spread hinders movement of occupants through the egress system. Particularly, in evacuation through stairways, the possibility of smoke entering the stairwell due to opening and closing of doors is very high [19]. High concentration of smoke can lead to blockage or loss of egress routes which adversely affects the egress capacity of a building.

It should be noted that in emergencies such as fire, situational awareness is an additional factor that influences evacuation. As previously discussed, situational awareness refers to the ability to assess in real time the response of occupants, structure and as well as the environment. The role of situational awareness is important through the entire duration of a fire incident or any disaster in a building. In the initial phases of fire development (refer Fig. 1), situational awareness provides the occupants with information such as location of fire, levels of temperature and smoke within the building, etc. that can assist in identifying accessible exit routes for faster evacuation. Additionally, in later stages of fire, situational awareness can also help evaluate the overall state (response) of the structure in terms of damage, available load carrying capacity and probable imminent collapse at any point during the disaster. This information can aid first responders in disaster response and firefighting operations.

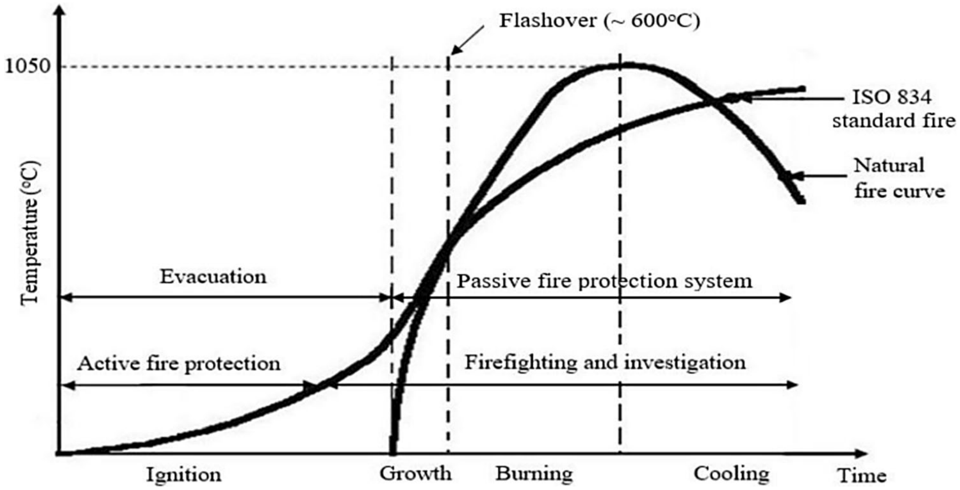

Figure 1. Fire development process in a typical compartment.

Situational awareness can be achieved by continuously monitoring key response parameters such as air temperatures and concentration of toxic gases in different compartments and temperatures and deformations in structural members through an interconnected network of sensors [12, 20]. Typically, data from these sensors needs to be analyzed through a processing system (wired or wireless) and subsequently transmitted to occupants and first responders to help in the decision making process. Daniel and Rein [20] proposed such a model and this model incorporates techniques such as data assimilation, inverse modelling and genetic algorithm using sensor data to predict the evolution of fire (such as smoke propagation and flame spread) in a building. A similar framework for implementing a cognitive abilities to built infrastructure and the associated limitations are also detailed in the paper by Naser and Kodur [12].

Human factors also play a significant role in evacuation during emergencies. Characteristics such as age, gender, physical disabilities, etc. affects the movement, evacuation speed and response of occupants. Detailed discussions on human behavior in fire can be found in chapters by Kuligowski and Gwynne and Boyce in the SFPE handbook [5]. This paper focuses on parameters pertaining to building and fire characteristics that have an impact on the process of emergency evacuation.

3. Evacuation Simulations

In order to examine the different geometric parameters of the egress components and quantify the positive impact of situational awareness, evacuation simulations during fire incident in a building are carried out using Pathfinder. The details of the building used for the simulations, validation and parametric studies are discussed in the following sections.

3.1. Description of Building and Evacuation Simulation

The building chosen for evacuation simulations correspond to a typical office occupancy structure in Denver, Colorado, USA [21] to simulate realistic conditions. The building is 32 story high with a story height of about 3.05 m (10 ft). The floor layout is rectangular and has a floor area of about 2675.61 m^2 (36.58 × 73.15 m) (28,800 sq. ft (120 × 240 ft)) (refer Fig. 2). The building has two staircases in the core of the building (represented as A and B in Fig. 2). Additionally, the building has six occupant elevators and two service elevators. For the purpose of this study, the building is assumed to have identical floors throughout its height and each floor is occupied with 250 occupants (refer Fig. 3). The assumed number of occupants fall slightly higher than that required for a typical business (or office) building (as per IBC 2018 [6]) and will represent a worst-case scenario for the evacuation studies. The percentage male and female occupants considered are 57% and 43% respectively [15]. All dimensions and arrangement of the egress components assumed in the building are in accordance to IBC 2018 [6].

The evacuation simulation is carried out using Pathfinder 2018.3.0730 [15]. This computer program allows modelling the movement of occupants within the structure while accounting for points of congestion, queuing and bottlenecks. Two modes, namely SFPE and steering, are offered by the software to model occupant motion. The first mode is based on the hydraulic model presented in the Society of Fire Protection Engineers (SFPE) handbook [5]. In this mode, occupant speed is controlled by density and the flow through the building is determined by the size of the egress components.

The verification and validation for this version of the software comprises of a detailed set of test cases designed to ensure that the simulations capture realistic behavior. The verification tests are synthetic tests that are specifically designed to examine the ability of the software to implement a particular evacuation mode or occupant behavior. Some of these tests include floor rate tests for each of the egress components, behavior tests that verify grouping behavior, merging, collision, etc. and speed tests [22]. Validation tests are based on published experimental data from the literature. These experiments include unidirectional and bidirectional flow in corridors, turning and merging behavior in T-junctions, etc. A more detailed description of these tests and results can be found in the Pathfinder verification and validation document [22].

The second mode, steering, is more advanced and realistic in simulating occupant movement [15]. This mode allows for modelling complex occupant behavior and route choice based on interaction between persons and collision avoidance. Unique characteristics may be assigned to individual occupants to implicitly simulate specific human behavior (response) during evacuation in an emergency. The steering mode in Pathfinder has been used in a number of evacuation studies [23–25] and also validated against field evacuation data reported in the literature.

3.2. Evacuation Analysis Using Hydraulic Model

As discussed earlier, the hydraulic model is a simple analytical tool to evaluate evacuation time for a given building (or an egress component). This model gives a

Figure 2. Typical floor layout with distribution of occupants. A, B: Required stairways as per IBC 2018 [6].

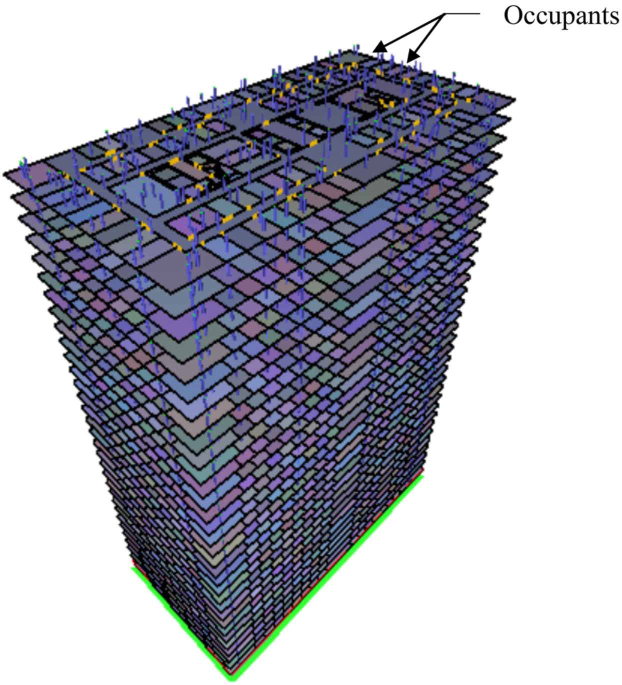

Figure 3. Side view of the 32 story high-rise building.

quick estimate of the egress performance and also a basis for carrying out more detailed assessment of different evacuation scenarios (like buildings with complex floor layouts, occupants with different demographics, etc.). In this study, the evacuation time for the building described in the previous section is obtained using the second-order approximation of the hydraulic model. All occupants are assumed to start egress at the same time and only stairways (not elevators) are used in evacuation. Figure 4 shows the dimensions of the different egress components considered for computing the evacuation time.

To track the egress flow in the building, the flow capability through the three points of transition, namely, corridors, doors and stairways are computed based on the following equations.

$$\text{Speed,} \quad S = k - akD \tag{1}$$

$$\text{Specific Flow,} \quad F_s = SD \tag{2}$$

$$\text{Calculated Flow,} \quad F_c = F_s W_e \tag{3}$$

where, D denotes population density in persons per unit area, W_e is the effective width of the egress component and a, k are constants defined in SFPE Handbook [5]. The egress component with the least flow capability (measured in terms of F_c) will govern the evacuation process.

The time (t_p) required by a population (P) to pass a point in the egress route with calculated flow (F_c) is given by

$$t_p = P/F_c \tag{4}$$

Using this approach, the evacuation time is found to be 84 min. The detailed calculations for computing the evacuation time using the hydraulic model can be found in the "Appendix". Many computer programs, including Pathfinder (SFPE mode) [15], have implemented the hydraulic model approach to evaluate the evacuation time from different types of occupancies in structures.

For crowded buildings, as in the case of the building analyzed here, the steering mode in Pathfinder allows to capture realistic occupant motion, including the time-consuming maneuvering that is required to get through the egress components with minimal wall–occupant and occupant–occupant collisions. Evacuation simulation of the building considered here, is conducted using the steering mode in Pathfinder. For this purpose, the building is modeled in AutoCAD and imported to the Pathfinder software. The simulation parameters for steering mode, namely, steering update interval and minimum flow rate factor are taken as 0.1 s and 0.1 respectively. The steering update interval controls how often (in simulation time) steering calculation gets updated. The higher the value the faster the simulation runs. However, it compromises on accuracy of the simulation as it affects the decision-making skills of the occupant. The minimum flow rate factor

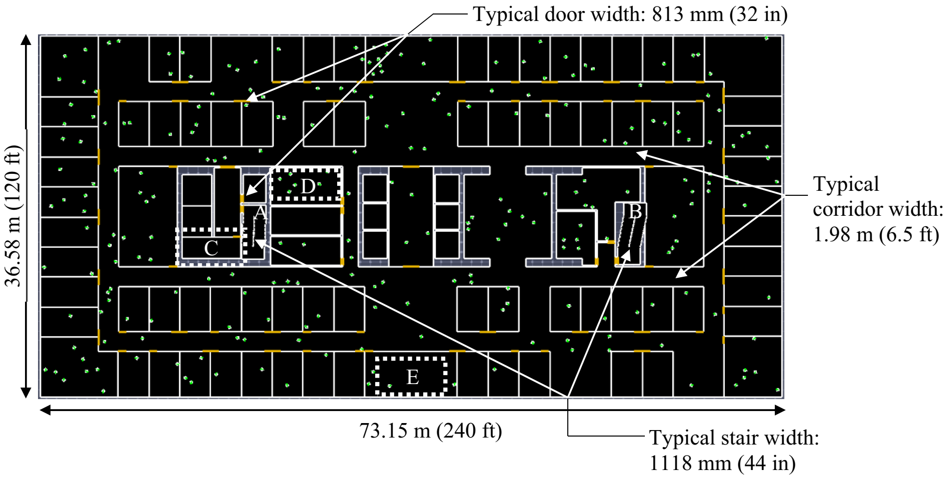

Figure 4. Floor layout with dimensions of different egress components. A, B: Required stairways as per IBC 2018 [6]. C, D, E: Possible locations for additional stairway.

is used when occupants are deciding which door to use when there are queues at the doors. A non-zero value will always show the queue near the door to be flowing and hence, prevents the occupants from switching doors when the flow rate is low. This is similar to the actual scenario during evacuation, as occupants in the building are typically not aware of whether or not the queue at a particular door is moving or not. The initial position of occupants in each floor are randomly assigned at the start of the analysis. All occupants are assumed to have a maximum (unimpeded) walking speed of 1.19 m/s (3.92 ft/s) in accordance to SFPE handbook guidelines [5]. The walking speed of occupants are automatically adjusted during the simulation based on population density and geometric characteristics of the egress components. Figure 5 shows the number of occupants remaining in the building as a function of time obtained using Pathfinder.

The time-history plot indicates that the occupants required 87 min to evacuate the building. It is seen that the evacuation time predicted by the software (using the steering mode) is close to the one that is obtained using the hydraulic model. All the simulations that are carried out for the parametric study uses the steering mode for modelling occupant movement.

3.3. Parametric Study

The parametric studies are broadly grouped into two parts. In the first part, evacuation simulations are carried out under normal conditions (evacuation drill conditions) to understand the effect of geometric parameters on occupant behavior and egress performance. In the second part, evacuation under real fire incident is simulated. The effect of implementing situational awareness during fire evacuation is also examined.

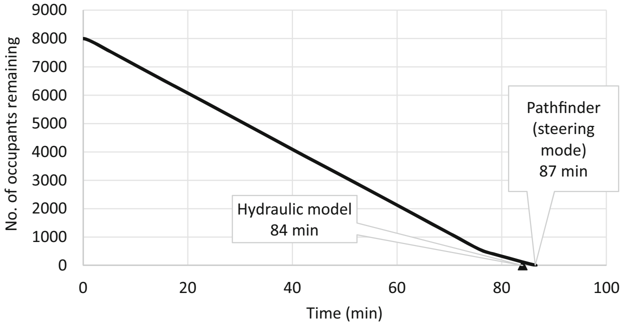

Figure 5. Comparison of evacuation time predicted using Pathfinder and hydraulic model.

3.3.1. Evacuation Drill Conditions

(a) Number of stories

The height of a building is a crucial factor that affects evacuation time. As the number of stories increases, occupants need to travel greater distances to exit the structure. The number of occupants also increases proportionally with increase in building height. For instance, with an occupant load of 250 per floor, a 40 story building will have 10,000 occupants as compared to 5000 in a 20 story building. The WTC twin towers that collapsed during the 9/11 attack were 110 stories tall with a full occupancy (theoretical) of around 50,000 people [26]. The IBC provisions for the number of stairways required were updated following 9/11 review for high-rise buildings. Expect for residential occupancy, all buildings that are more than 128 m (420 ft) in height need one additional stairway more than the minimum required as per the occupancy load per story [6]. The redundant stairway is treated similar to the other stairways and is permitted to be used under normal conditions. Though there is a significant increase in the total number of occupants with building height, the minimum number of stairways continues to be dependent only on the occupant load per story. It is not known whether one additional stairway will be sufficient for timely evacuation from skyscrapers (buildings exceeding 128 m (420 ft) in height), especially in the event of an emergency. Evacuation simulation of buildings with 4 different number of stories is conducted. The floor plan with three stairways (A–B–C) is adopted for this study.

The results show that the increase in time required to evacuate the building can be significantly longer as the height of the building increases (refer Fig. 6). The evacuation time almost doubles when the number of stories increases from 40 to 80. About 291 min (more than 4.5 h) is required for evacuation in the case of the 80 story building with 3 stairways under normal conditions. Further, in the event of a fire, the evacuation time is bound to increase [5]. It is evident from this study that the provision of one additional stairway in excess of the minimum requirements may not be sufficient for evacuating occupants from skyscrapers. Alternate means of egress need to be provided to ensure timely evacuation. According to

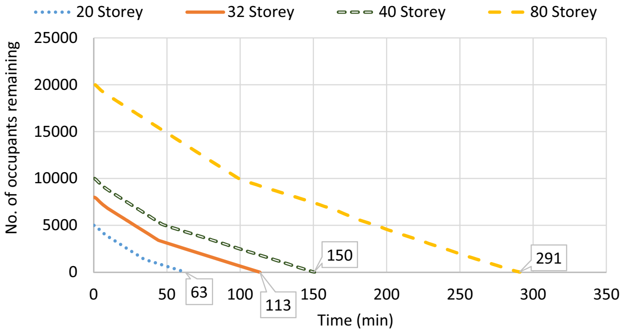

Figure 6. Evacuation time with different story heights.

NFPA 101 [27], for stairs in new buildings serving 2000 or more occupants (from all stories above the level where the stair is considered), the minimum width of the stairway needs to be 1420 mm (56 in.). For buildings with 32, 40 and 80 stories, the stairways in the lower levels are likely to fall under this category. The evacuation times simulated are likely to improve if NFPA provisions for stairway width is adopted in these buildings.

(b) Location of stairways

Stairway location in a high-rise building is one of the primary parameters that is considered in the design of the egress system. The layout of stairways tends to affect occupant behavior during emergency evacuation. Kobes et al. [8] noted that the choice of route that the occupants use depends on the location and accessibility of the exit stairways, complexity and familiarity with the egress layout. As per IBC 2018 [6], the stairway arrangement is decided based on the distance that the occupants need to travel to reach the nearest stairways in a given floor. The maximum travel distance is restricted to 22.9 m to 38.1 m (75 ft to 125 ft) based on the type of the occupancy [6]. However, this distance does not account for the considerable number of floors that occupants need to travel before exiting the building. Further, IBC 2018 also requires two stairways in a building to be spaced from each other at a distance not less than 9.14 m (30 ft) or not less than one-fourth of the maximum diagonal distance of the building, whichever is lesser. This building code, however, does not stipulate a minimum separation distance for any additional stairways that may be required in high-rise buildings (exceeding 128 m (420 ft) in height). In this study, three different stairway arrangements (which are allowed as per IBC 2018 [6]) are considered (see Fig. 4). The location of stairways is such that the maximum travel distance from any occupiable point on the floor to the closest exit is 100 ft. This follows the IBC 2018 [6] provisions for business buildings with sprinkler system. In two of the cases (A and B), all the three stairways are placed within the building core (as in the case of collapsed WTC twin towers). In the third case (C), evacuation with one of the stairways located outside the core is examined. Though the position of stairway E is shown within the building, it is always possible to locate the stairway outside the building layout to avoid loosing occupiable floor area. It is assumed that the difference in the evacuation time between the two positions will not be significant.

Figure 7 shows that the evacuation time is maximum in case A (where two of the stairways are located close to each other). It should also be noted that the time to evacuate in this case is greater than that required when only two stairways are present (see Fig. 7). The possibility of an increase in congestion (or potential blockage) due to the addition of a stairway needs to be considered while designing the egress system. Additionally, in case A, there is a common wall between the two of the staircases, A and C. From a fire incident point of view, any damage to the wall will affect both the stairways and hence impact the exit capacity of the building. Cases B and C give similar evacuation times of about 67 min and 74 min respectively. Stairways are often located within the building core (as represented by case B (A–B–D)) due to economic reasons. As the core is centrally positioned, stairways that are present within the core are equally accessible from all sides of the building, and hence reduce the travel distances of the occupants. During fire incidents or other emergencies, blockage of one of the stairways (and the exit route) can be handled more effectively by using a stairway arrangement with greater separation distance (or remoteness). From this perspective, it is beneficial to consider the possibility of positioning one stairway outside the core (as shown in case C (A–B–E)).

(c) Number of stairways

The number of stairways required in a high-rise building is determined as a function of the occupant load per story. The IBC 2018 provisions requires a minimum of two stairways when the occupant load per floor is 500 or less [6]. An increase in the occupant load per story necessitates a higher number of stairways. As the stairways can utilize some amount of occupiable floor area in every story, increasing the number of stairways throughout the building height can be uneconomical. In this study, the number of stairways is increased only in the lower section of the building where the amount of congestion is expected to be high during evacuation. It is assumed that the occupants are familiar with the additional stairway and will relocate when they reach the lower levels of the building. Four cases are examined; two stairways; three stairways (A–B–D); three stairways in bottom 16 stories; and three stairways in bottom 8 stories.

Results from numerical study (see Fig. 8) indicate that the evacuation time is minimum for the case with 3 stairways (about 23% reduction in evacuation time as compared to 2 stairways). A greater number of stairways, when carefully located such that no congestion occurs, increases the exit capacity of the building. This can allow for more occupants to be evacuated in a given duration of time. In this study, it is noted that the amount of queuing that occurs in the lower floors are much higher as the entire evacuating population from the higher stories need to pass through the lower level stairs. From the results for the last two cases, providing additional number of exits in the lower part of the building helps reduce the congestion/queuing in the lower floors. The case where 2 stairways are pro-

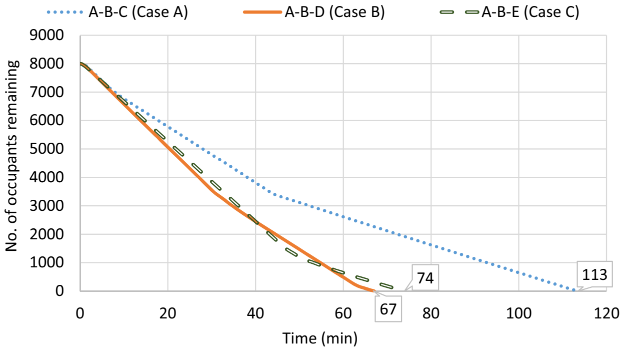

Figure 7. Evacuation time for different locations of stairways.

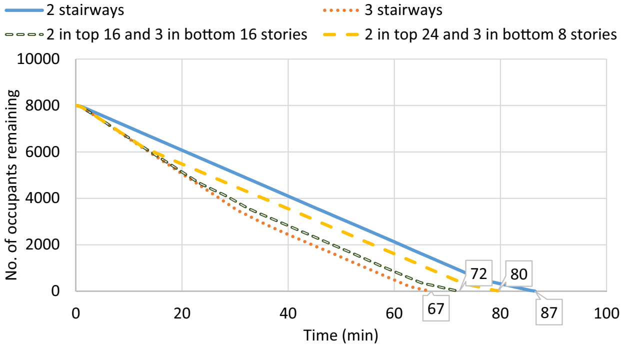

Figure 8. Evacuation time with different number of stairways.

vided in the top 16 stories, whereas, 3 stairways in the bottom 16 stories is found to be the optimal case that results in 17% reduction in evacuation time. The total evacuation time in this case is almost similar to that in the case of three staircases provided in all the stories. Such a design will also be an economically more viable option than increasing the number of stairways throughout the building height. However, it is noted that in a real-life situation, people will tend to stay in the same stairway that they started in and may not move to the additional stair when they reach the lower levels of the building. Hence, these scenarios will be more appropriate when situational awareness is considered and a methodology is developed to have occupants selectively relocate to the additional stairway. Evacuation under these scenarios with situational awareness is discussed in the later part of this paper.

(d) Stairway width

The width of the stairway directly determines its capacity and controls the flow of persons passing through the stairway at any given time. Stairway width is a function of occupant load per story. If a higher fraction of the occupants tends to use the stairways, sufficiently increased width of stairs is necessary. The IBC 2018 requires that the minimum clear width of stairways to be 1118 mm (44 in.) [6], except, if the occupant load served by the stairway is 49 or less, the code allows the use of 914 mm (36 inch) stairway. While evacuating using stairways, people maintain a boundary layer clearance (between themselves and the wall faces) and only the middle portion of the stairways is effectively used [5]. Often, other projections present within the stairways (such as handrails, etc.) also affect the effective width used during evacuation. In a fire situation, stairways are prone to be affected by smoke, especially near the floors that are exposed to fire [5]. Increased width of stairs can accommodate increased rows of evacuees and also counterflow that may occur during emergency evacuation. In this study, the stairway width is varied and the evacuation time in each of the scenarios is studied. Three stairway widths are examined; minimum required width (1118 mm (44 in.)), 25% increased width (1397 mm (55 in.)) and 50% increased width (1676 mm (66 in.)). 3 stairways with configuration A–B–C is adopted.

Typically, stairways with a width of 1118 mm (44 in.) is considered to accommodate two separate files of occupants comfortably, with 559 mm (22 in.) for each file. The choice of 25% increase in stairway width (leading to 1397 mm (55 in.) wide stairways) is considered with a view of accommodating an intermediate staggered file of occupants in addition to the existing two files of occupants. A 50% increase in stairway width (resulting in a 1676 mm (66 in.) wide stairway) will have 559 mm (22 in.) in excess of 1118 mm (44 in.) and can comfortably accommodate three files of occupants. The present study adopts the default occupant profiles available in Pathfinder where occupants are modeled as upright cylinders with a maximum width of 460 mm and height of 1.8 m. The dimensions of the occupants support the idea of realistically accommodating the additional person (or a staggered file) when the stairway width is increased by 25% and 50%.

Results plotted in Fig. 9 indicate that an increase in stairway width by 25% and 50% lead to 10% and 30% reduction in evacuation time respectively. Although increasing the size of stairway significantly reduces the evacuation time, providing additional stairways or alternate means of egress is more beneficial under fire events. In this way, loss of one of the stairways will not greatly reduce the exit capacity of the building. In certain buildings, the stairways in a given floor may not always be of equal width. Stairways of different width are employed in high-rise buildings with a view to provide access for large items (such as furniture, etc.) or for aesthetic purposes. However, in the event of loss of the bigger stairway due to fire, the available exit capacity of the building may be significantly reduced. It is important to consider this aspect while designing unevenly sized stairways for evacuation.

3.3.2. Fire Conditions

(a) Fire location

The location of fire within a building is critical while studying evacuation times and efficiency. Fire location directly affects the portion of the building (or the

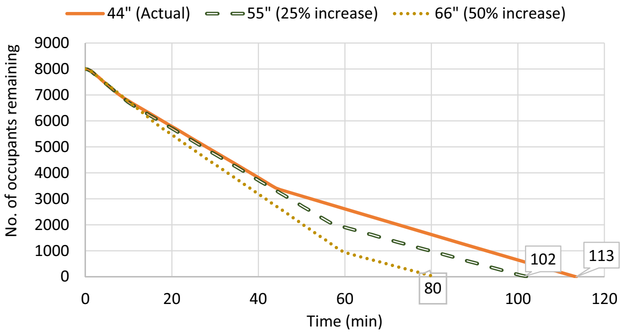

Figure 9. Evacuation time for different width of stairways.

egress route) that can be safely used by the occupants, as well as first responders during evacuation. Although the actual presence of fire may be contained to one (or more than one) floor, the effect of smoke spread can affect other stories as well [5]. This leads to unsafe egress paths (or blockage) in floors near the fire location that delays the process of evacuation. This study examines 3 fire locations along the building height; lower section (in between floors 3 and 6), mid-section (in between floors 12 and 15) and upper section (in between floors 25 and 28). Staircase A is considered to be blocked (i.e. inoperable for occupants) between the corresponding floors in each case due to high concentration of smoke after a few minutes of fire.

The time history plot (Fig. 10) shows that the total evacuation time, when fire is present in the lower section of the building, is 55% and 20% higher than that when fire is in upper and middle sections respectively. The larger queuing and congestion in the lower stories due to inaccessible stairway (A) is the cause of longer evacuation time. As per statistics in NFPA report [4], most of the fires begin in the lower floors of high-rise buildings, especially in the case of office occupancy. Additionally, prior studies have shown that buildings that experience fire in the lower floors are prone to higher damage (and potential collapse). As a result, the available time for evacuation (or response operation) is reduced. The location of potential fire in the lower section of the building should, hence, be treated as a critical case while designing the egress system.

(b) Situational awareness

In order to evaluate the influence of situational awareness, two scenarios are compared. In the first scenario, the time for evacuation is estimated in the event of a fire breakout. Fire is assumed to originate between floors 3 and 6 and the resulting smoke spreads vertically blocking stairway A between these floors. The behavior and route choice of individual occupants are suitably modified to account for evacuation under fire conditions with and without situational awareness. In the simulation model, the occupant behavior is defined such that the occupants continue using the nearest egress path for evacuation. Upon reaching

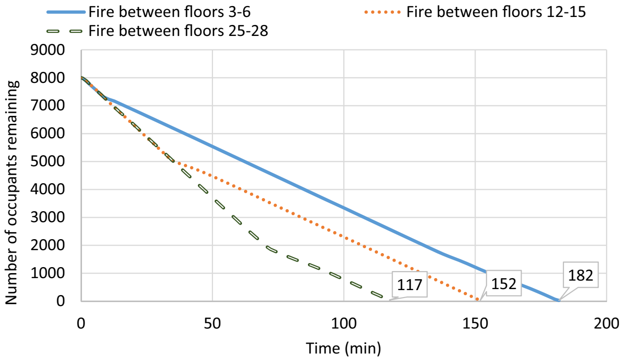

Figure 10. Evacuation time with different fire locations.

the sixth floor, the occupants trying to continue using stairway A understand (on their own) that the stairway A is blocked. Some delay is expected from the time taken by the occupants in evaluating (realizing) the situation and proceeding to the next nearest exit. In the second scenario, the same fire incident is assumed. However, the occupants are now equipped with situational awareness where the status of fire growth and spread is continuously updated. To simulate this behavior, the occupants are updated with the information regarding the blockage in stairway A between stories 3 and 6. During the simulation, the occupants directly avoid using stairway A between stories 3 and 6, and use other available exits in those levels to evacuate. In all other stories, occupants make use of all the three stairways. Figure 11 compares the evacuation time simulated with and without accounting for situational awareness when 2 and 3 stairways are provided in the building. The duration of evacuation during fire drill is also plotted.

In the building where only two stairways are used, blockage of one of the stairway in the lower section of the building due to fire breakout results in very long queues. The evacuation time increases to 182 min during the fire event as compared to 87 min in the fire drill scenario (when there is no blockage of stairs). If the situational awareness provisions are incorporated in the building only results in 5% reduction in evacuation time is obtained. The delay that is caused due to queuing is more significant than that which results from occupants trying to evaluate and locate the available exit in the affected stories. When three stairways are provided throughout the building height, the evacuation time during the fire event is 35% lesser than in the case of two stairways. In addition, accounting for situational awareness is seen to result in a further 22% reduction in evacuation time, during a real fire incident.

The effect of situational awareness, while using an increased number of stairways in the lower portion of the building, is also evaluated. In case A, three stairways are provided in the lower 16 stories of the building, whereas, in case B, three stairways are provided in the lower 8 stories alone. When the evacuation simulation is carried out under fire conditions without accounting for situational awareness, results from Fig. 12 shows that there is a significant reduction in evacuation

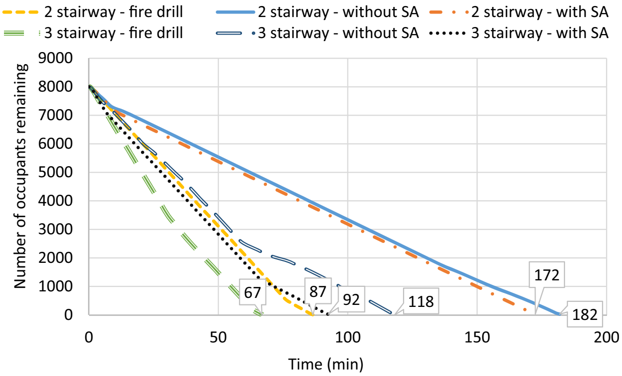

Figure 11. Evacuation simulation with uniform number of stairways and situational awareness (SA).

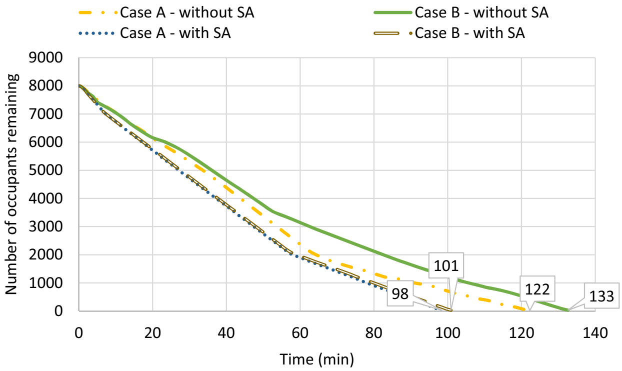

Figure 12. Evacuation simulation with non-uniform number of stairways and situational awareness (SA).

time (32% and 27%) in cases A and B as compared to the case of two stairways provided throughout the height of the building. When situational awareness is incorporated in the building, evacuation time further reduces by 20% and 24% respectively in cases A and B. Further, from Figs. 11 and 12, it can be seen that the evacuation time obtained with situational awareness in cases A and B (98 min and 101 min respectively) is very close to that when 3 stairways are used through all stories (92 min). Using a higher number of exits in the lower stories is a better alternative even under the event of fire breakout and blockage of exits, when situational awareness is implemented.

Table 1 summarizes the different cases considered in the parametric study and the respective evacuation times obtained from the numerical simulations.

Table 1
Evacuation Time for Different Cases Considered in the Parametric Study

Varied parameter	Cases	Stairways used	Evacuation time (min)
Evacuation drill (during normal conditions)			
Number of stories	20 stories	A–B–C	63
	32 stories	A–B–C	113
	40 stories	A–B–C	150
	80 stories	A–B–C	291
Location of stairways	Three stairways within core	A–B–C	113
	Three stairways within core	A–B–D	67
	Two stairways within core and one outside core	A–B–E	74
Number of stairways	Two stairways	A–B	87
	Three stairways	A–B–D	67
	Two in top 16 and three stairways in bottom 16 stories	A–B in top 16 and A–B–D in bottom 16 stories	72
	Two in top 24 and three stairways in bottom 8 stories	A–B in top 24 and A–B–D in bottom 8 stories	80
Stairway width	1118 mm (44 in.)	A–B–C	113
	1397 mm (55 in.)	A–B–C	102
	1676 mm (66 in.)	A–B–C	80
Evacuation during fire incidents			
Fire location	Fire occurring in between stories 3 to 6	A–B	182
	Fire occurring in between stories 12 to 15	A–B	152
	Fire occurring in between stories 25 to 28	A–B	117
Without situational awareness (fire occurring in between stories 3 to 6)	Two stairways	A–B	182
	Three stairways	A–B–D	118
	Two in top 16 and three stairways in bottom 16 stories	A–B in top 16 and A–B–D in bottom 16 stories	122
	Two in top 24 and three stairways in bottom 8 stories	A–B in top 24 and A–B–D in bottom 8 stories	133
With situational awareness (fire occurring in between stories 3 to 6)	Two stairways	A–B	172
	Three stairways	A–B–D	92
	Two in top 16 and three stairways in bottom 16 stories	A–B in top 16 and A–B–D in bottom 16 stories	98
	Two in top 24 and three stairways in bottom 8 stories	A–B in top 24 and A–B–D in bottom 8 stories	101

4. Limitations and Future Studies

The focus of the study is limited to comparing the geometric parameters of the egress system to enhance the efficiency of egress performance. The likely change in evacuation time that can be achieved from adopting different alternatives to the egress design (such as change in stairway width, number of stairways or adopting advanced techniques like situation awareness for emergency evacuation) is quantified. Results from this study can provide insights to practitioners for the development of architectural layouts of high-rise buildings. Specific attention is given to stairway evacuation under emergencies. However, the performance of other egress components such as elevators, refuge floors, etc. have not been addressed. The study also does not account for occupant demographics and fatigue behavior. The mode of evacuation considered in this study is limited to total evacuation where all occupants in the building are assumed to evacuate simultaneously. The implementation of other evacuation strategies such as phased or delayed evacuation and, the impact of these modes on evacuation time in a high-rise building will be considered in the future studies.

The future research needs in high-rise building evacuation is to include the effects of evolving fire scenarios and structural response on occupant behavior. In addition, the human-building interaction can be explicitly modeled, especially under fire conditions. From this study, it is inferred that accounting for situational awareness can reduce the evacuation time during emergencies. However, the practical applicability of this concept faces serious challenges including development of sensors, power and data mining requirements that needs further research. More details on the current limitations in realizing cognitive structures can be found in the article by Naser and Kodur [12].

5. Conclusions

Based on the results presented in this paper, the following conclusions are drawn:

1. Evacuation time in high-rise buildings is highly influenced by the geometric parameters of the egress system including number of stairways, their location and width.
2. Among the geometric parameters analyzed, the location of stairways influences the evacuation time the most. The reduction in evacuation time is highest (about 40%) when the location of the stairways is changed from A–B–C to A–B–D, owing to the decrease in travel distances and congestion offered by the latter configuration.
3. Under fire conditions, the evacuation time is seen to be critically affected when the fire occurs in the lower levels of the building. Fire occurring in between stories 3 and 6 in a 32 story building with two stairways is seen to have the maximum evacuation time of 182 min.
4. In the case of skyscrapers, providing one additional stairway in addition to the minimum requirements (as per IBC 2018 [6]) may not be fully effective in achieving timely evacuation of occupants. Total evacuation from a 40 story

building using three stairways is found to take 2.5 h, whereas, the evacuation from a building with 80 stories takes about 4.5 h.

5. Increasing the number of stairways may not always reduce the evacuation time if the location of the additional stairway increases congestion. While an evacuation time of 87 min is obtained by using two stairways (A–B), the three stairs configuration A–B–C resulted in an evacuation time of 113 min.
6. Providing a higher number of stairways (or exits) in the lower section of the building alone is found to considerably reduce the evacuation time. A reduction in evacuation time of 32% and 27% is obtained by introducing an additional stairway in the lower half and lower quarter of the building respectively.
7. Updating occupants with situational awareness during emergencies is shown to improve the efficiency of evacuation. Up to 24% reduction in evacuation time was achieved when situational awareness is implemented in evacuation of a 32 story building.

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Appendix

The computation of evacuation time of the building evaluated in this study using the hydraulic model is carried out in the following steps. Refer to Fig. 4 for dimensions of the egress components.

Flow Capacity of Corridors

Effective width, $W_e = 1981 - (2 \times 152) = 1677\,\text{mm}(5.5\text{ft})$

Density, $D = 125\,\text{persons}/245\ \text{m}^2(125\,\text{persons}/2635\ \text{ft}^2)\text{corridor area}$ $= 0.51\,\text{persons}/\text{m}^2\left(0.047\,\text{persons}/\text{ft}^2\right)$

As the density is less than 0.54 persons/m^2 (0.05 persons/ft^2), all occupants will have a speed (S) of 1.19 m/s (235 ft/min) [5].

Specific flow, $F_s = SD = 0.607\,\text{persons/s/m}(11.139\,\text{persons/min/ft})$ effective width (governs)

Maximum specific flow, $F_{sm} = 1.3\,\text{persons/s/m}(24\,\text{persons/min/ft})$ effective width [5]

Calculated flow for the corridors, $F_c = F_s \times W_e \approx 61\,\text{persons/min}$

The calculated flow (Fc) is an initial value for the corridors and can be sustained only if the next transition point (stairway doors) can accommodate this flow.

Flow Capacity of Stairway Doors

Effective width, $W_e = 813 - 305 = 508\,\text{mm}\,(20\,\text{in.})$

Specific flow, $$F_{s(door)} = \frac{F_{s(corridor)} W_{e(corridor)}}{W_{e(door)}} = \frac{0.607 \times 1677}{508}$$

$$= 2\,\text{persons/s/m}\ (36.76\,\text{persons/min/ft})\ \text{effective width}$$

Maximum specific flow, $F_{sm} = 1.3\,\text{persons/s/m}\,(24\,\text{persons/min/ft})$ effective width [5] (governs)

Calculated flow for the corridors, $F_c = F_{sm} \times W_e \approx 40\,\text{persons/min}$

As $F_{c(door)} < F_{c(corridor)}$, queuing of occupants occurs at the doorway entrance.

Rate of queue buildup is $61 - 40 = 21$ persons/min

Flow Capacity of Stairways

Effective width, $W_e = 1118 - 305 = 813\,\text{mm}\,(32\,\text{in.})$

Specific flow, $F_{s(stairs)} = \frac{F_{s(door)} W_{e(door)}}{W_{e(stairs)}} = \frac{1.3 \times 508}{813}$

$= 0.822\,\text{persons/s/m}\,(15.04\,\text{persons/min/ft})$ effective width (governs)

Maximum specific flow, $F_{sm} = 1.01\,\text{persons/s/m}\,(18.5\,\text{persons/min/ft})$ effective width [5]

Density, $D = 1.1\,\text{persons/m}^2\left(0.1\,\text{persons/ft}^2\right)$

Speed, $S = k - akD = 1.08 - 0.266 \times 1.08 \times 1.1 = 0.76\,\text{m/s}\,(149.6\,\text{ft/min})$

Length of stairways on each floor, $L = 9.67\,\text{m}(31.73\,\text{ft})$

Time to descend from one floor to another is $\left(\frac{9.67}{0.76}\right) = 0.21\,\text{min}(13\,\text{s})$

After 13 s, 8 ($\approx 0.21 \times 40$) occupants will be in each stairway to produce a total of 256 ($= 8 \times 32$) occupants in all the floors. The remaining 117 ($= 125 - 8$) occupants will remain in queue in front of each stairways.

In each of the floors, merging of stairway flow and stairway entry flow occurs.

Merging flow, $$F_{s(out-stairs)} = \frac{\left[F_{s(door)} W_{e(door)} + F_{s(in-stairs)} W_{e(in-stairs)}\right]}{W_{e(in-stairs)}}$$

$$= \frac{(1.3 \times 508) + (0.822 \times 813)}{813} = 1.63\,\text{persons/s/m}(30.08\,\text{persons/min/ft})\ \text{effective width}$$

Maximum specific flow, $F_{sm} = 1.01\text{persons/s/m}\,(18.5\,\text{persons/min/ft})$ effective width [5] (governs)

Calculation of Evacuation Time

Under normal conditions, a duration of 0.5 min is assumed to be required for the flow of occupants to reach the stairway door [5]. This is a conservative estimate as the exit stairways are placed at an average distance of 22.86 m (75 ft) from all the occupants and the occupants are moving at a speed of 1.19 m/s (235 ft/min). At the end of 43 s (30 s + 13 s), 256 occupants will occupy the stairways.

Time taken by the end of flow to reach the 31st floor

$$= 43 + \left(\frac{117}{40}\right) \times 60 + 13 = 231.5\,\mathrm{s}$$

Similarly, the time taken for the flow to reach the each of the lower floors can be added to obtain the total time required for all the occupants to exit the building.

Evacuation time $= 231.5 + \left[\left(\frac{117}{0.813 \times 1.01}\right) + 13\right] \times 31 = 5052\,\mathrm{s}$ (84.2 min)

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