PROCEEDINGS, Fire and Evacuation Modeling Technical Conference (FEMTC) 2018
Gaithersburg, Maryland, October 1-3, 2018

The Impact of Stairwell Queues on Egress Time From a Floor

Christopher K. Campbell, PE

Arup
1120 Connecticut Ave NW Suite 1110
Washington, DC, 20036, USA
Christopher.Campbell@Arup.com

ABSTRACT

Current model building codes contain requirements for (1) the minimum number of exits and (2) the minimum egress capacity from a space, both based upon the occupant load served. These requirements largely remain consistent for all spaces in a building, regardless of the height or number of stories. There is some research that indicates an inefficiency during occupant traversal of exit stairwell landings, specifically during a merging event of flows of occupants from the floor and the stair above. Both within exit stair enclosures and at the door leading to the exit stair, this inefficiency can lead to queues that form more quickly than the predicted by the hydraulic model egress correlations given in the SFPE Handbook. This study uses an egress model to predict the time for occupants to clear a story and enter an exit stair across buildings of various heights. It was found that the mean and maximum times for occupants to clear a given floor and enter an exit stair is directly proportional to the number of stories in the building.

INTRODUCTION

In the United States and many other countries, the International Building Code (IBC) is the most commonly enforced model code. Some jurisdictions within these countries also enforce NFPA 101, Life Safety Code, for provisions related to building use and occupancy and the sizing of means of egress. While both of these codes have provisions for performance-based design related to means of egress, they are often applied and enforced as prescriptive codes. Key design requirements related to egress such as number of exits and egress width are primarily a function of the number of occupants in a space.

Both the IBC and NFPA 101 have prescriptive requirements for egress width based on number of occupants. For most occupancy types, both codes require 0.3 inches of egress width per occupant for stairs and 0.2 inches of egress width per occupant for doors, corridors and other level components (IBC 1005.3, NFPA 101 7.3.3). The IBC allows a reduction of these factors to 0.2 inches per occupant for stairs and 0.15 inches per occupant for level components when the building is fully sprinkler-protected. NFPA 101 allows a reduction of the egress width factor for stairs wider than 44 inches according to Equation 1.

$$C = 146.7 + \left(\frac{W_n - 44}{0.218}\right) \qquad \text{(Equation 1)}$$

Where:
C = capacity in persons, rounded to the nearest integer
W_n = nominal width of the stair (in.)

Both codes also have prescriptive requirements for the number of means of egress based on the number of occupants. For example, as shown in Table 1, the IBC has a minimum requirement of 2, 3, or 4 exits from each story, depending upon the occupant load. NFPA 101 has the same requirements based on the occupant load of each story (NFPA 101 7.4.1).

Table 1: Minimum number of exits or access to exits per story (IBC Table 1006.3.1)

Occupant Load Per Story	Minimum Number of Exits or Access to Exits From Story
1-500	2
501-1,000	3
More than 1,000	4

In both the IBC and NFPA 101, there are a number of other factors that could necessitate additional exits. These factors include exit access travel distance, common path of egress travel, dead-end corridors, exit remoteness and others that are outside the scope of this study. While these factors relate to the horizontal configuration of a building (i.e. horizontal travel across a given story), they do not explicitly relate to the vertical characteristics of a building, such as the building height or number of stories. In fact, in both the IBC and NFPA 101, the only exit requirement specifically related to a building's vertical characteristics is a requirement for one additional exit beyond what is required in Table 1 for buildings over 420 feet in height (IBC 403.5.2).

The abundance of egress requirements related to the horizontal configuration of a building and relative absence of requirements related to the vertical configuration are consistent with the overall evacuation strategy implicit in these codes. Both the IBC and NFPA 101 have requirements intended to protect the integrity of exit enclosures by means of fire-resistance rated construction, smokeproof enclosures, limitations on openings and penetrations, and strict limitations against storage and combustible materials located within the exit. These requirements force building designers to give occupants reasonable access to an exit enclosure and then protect those occupants within the exit enclosure until they reach the exit discharge. However, in most high-rise buildings, the majority of an occupant's evacuation time is spent on the exit stair (the vertical egress component), and it is reasonable to expect that occupant movement within the exit stair would be different for a low-rise building then for a high-rise building. Still, the code requirements for number of exits and egress width remain the same in both cases.

The motivation for the research presented herein is twofold: (1) the seeming lack of consideration of the impact of building height and number of stories on egress requirements in model building codes and (2) previous research on occupant movement during egress from high-rise buildings.

PREVIOUS RESEARCH

A primary reference in the analysis of egress from buildings is the "Employing the Hydraulic Model in Assessing Emergency Movement" chapter in the SFPE Handbook (Gwynne). The authors of this chapter define a hydraulic model that can be used to estimate the evacuation time from a building. The hydraulic model is based on a simplification of egress behavior and uses a set of equations for occupant velocity and occupant flow rate to estimate evacuation time. One of these equations, shown as Equation 2 below, defines the relationship between occupant flow rates during the merging of flows at a transition point (Gwynne, Equation 59.13). There are numerous instances of merging flows during a building evacuation, but one example is the merging of the flow of occupants travelling down a stair with the flow of occupants entering the stair on a landing.

$$F_{s(out)} = \frac{F_{s(in-1)}W_{e(in-1)}+F_{s(in-2)}W_{e(in-2)}}{W_{e(out)}} \qquad \text{(Equation 2)}$$

Where:
$F_{s(out)}$ = specific flow departing from a transition point (p/s-m)
$F_{s(in-1)}$ = specific flow value for one of the arriving flows at a transition point (p/s-m)
$F_{s(in-2)}$ = specific flow value for the other arriving flows at a transition point (p/s-m)

$W_{e(in-1)}$ = effective width of the route element serving $F_{s(in-1)}$ prior to transition point (m)
$W_{e(in-2)}$ = effective width of the route element serving $F_{s(in-2)}$ prior to transition point (m)
$W_{e(out)}$ = effective width after passing transition point (m)

The hydraulic model also defines a maximum specific flow, F_{sm}, which is the maximum flow rate possible through a particular type of exit route element. If the calculated value of $F_{s(out)}$ in Equation 2 exceeds F_{sm}, a queue will form on the incoming side of the transition point. However, if the maximum specific flow is not exceeded, then no queue will form. In this case, the specific flow can be converted to the calculated flow by combining Equation 2 and Equation 3 (Gwynne, Equation 59.8).

$$F_c = F_s W_e \qquad \text{(Equation 3)}$$

Where:
F_c = calculated flow (p/s)
F_s = specific flow (p/s-m)
W_e = effective width (m)

This yields a simplified flow relationship for transition points where queuing does not occur, shown in Equation 4.

$$F_{c(out)} = F_{c(in-1)} + F_{c(in-2)} \qquad \text{(Equation 4)}$$

Where:
$F_{c(out)}$ = calculated flow departing from a transition point (p/s)
$F_{c(in-1)}$ = calculated flow value for one of the arriving flows at a transition point (p/s)
$F_{c(in-2)}$ = calculated flow value for the other arriving flows at a transition point (p/s)

Equation 4 predicts that the sum of the flows arriving at a transition point is equal to the outflow departing that transition point, assuming no queuing occurs. However, there is some empirical research indicating an inefficiency that exists in the merging of the flow of occupants travelling down a stair with the flow of occupants entering the stair on a landing. A study of evacuation drill videos from four high-rise buildings found that for merging events without queuing, the mean flow rate departing the transition point was 75% of the sum of the flow rates entering the transition point (Campbell). This same study also showed that the time for occupants to traverse the stair landing increased 50% on average.

This research indicates an inefficiency in non-queued merging events on stair landings that results in the flow rate departing the event being less than what is predicted by the hydraulic model. Additionally, though this observed inefficiency was limited to non-queued merging events, one conclusion of that research was that the inefficiency leads to queuing more quickly than would otherwise be expected from the hydraulic model.

When considering this merging inefficiency occurring on every stairwell landing during an evacuation from a high-rise building, the multiplicative effect would likely be strong. Logically, it seems that as the number of merging events in an evacuation increases, the more this observed inefficiency will impact egress times, both from the building and from each story. The aim of this work is to compare egress time from similar buildings of various heights to determine if there is an observable relationship between the number of stories and the egress time, specifically the egress time from a story.

EGRESS MODELLING APPROACH

A sample building geometry was created using the Pathfinder 2018 egress modelling software. Egress simulations were performed using the sample geometry for buildings ranging from 2 to 12 stories. The typical floor geometry is shown in Figure 1. For each simulation, an identical story was added to the model geometry up to 12 stories, as shown in Figure 2. Each story was constructed 100 feet by 100 feet for a total area of 10,000 square feet. Each stairwell landing was constructed 4 feet by 8 feet, and the total floor to floor height was 11 feet. The stairs were 7-inch risers with an 11-inch tread and 44-inch width. The doors into each stair were 33 inches wide, as were the exit doors at the lowest level of each stairwell (not shown in Figure 1). An occupant load factor of 1 occupant for every 100 square feet was assigned to each story, for a total occupant load of 100 occupants per story. The 1:100 occupant load factor is consistent with the occupant load factor for business uses found in both the IBC and NFPA 101. Both exit stairs were available to all occupants on a given story, however occupants on Level 1 were assumed to have access to exits leading directly to the exterior of the building and were not considered in the analysis. The simulations were conducted as full-building evacuations and all occupants were assumed to start evacuating at the same time.

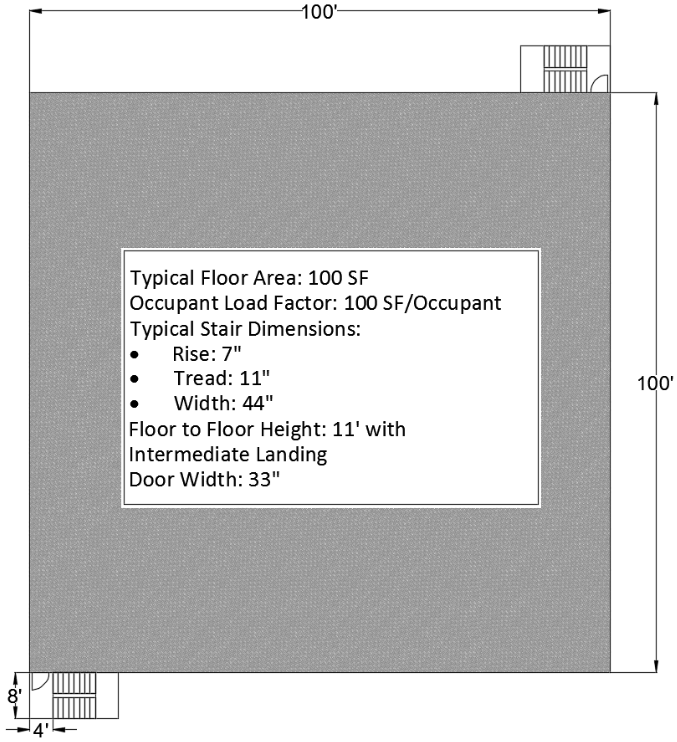

Figure 1: Geometry of egress model typical floor.

Each simulation was performed twice, once using SFPE mode and once using Steering mode. SFPE mode seeks to replicate the parameters of the hydraulic model described previously. Steering mode, as defined in the Pathfinder technical reference guide, "is based on the idea of inverse steering behaviors. Steering behaviors were first presented in Craig Reynolds' paper "Steering Behaviors For Autonomous Characters" (Reynolds) and later refined into inverse steering behaviors in a paper by Heni Ben Amor (Amor). Pathfinder's steering mode allows more complex behavior to naturally emerge as a byproduct of the movement algorithms - eliminating the need for explicit door queues and density calculations" (Thunderhead).

In both simulation modes, all model parameters were left in their default settings. The maximum walking speed was limited to 3.9 feet/second. Table 2 and Table 3 show the simulation mode parameters for SFPE mode and Steering modes, respectively.

Table 2: SFPE mode simulation parameters.

Parameter	**Setting**
Max Room Density	0.330 persons/ft^2
Boundary Layer	6 inches
Door Flow Rates	Use Calculated Specific Flow

Table 3: Steering mode simulation parameters.

Parameter	**Setting**
Steering Update Interval	0.1 seconds
Minimum Flowrate Factor	0.1
Collision Handling	On
Limit Door Flow Rate	Off

Leaving the Steering mode parameter to limit door flow rates "off" allows the steering algorithm to estimate the flow rate through door based on occupant behavior and not a maximum flow rate as specified in the SFPE mode.

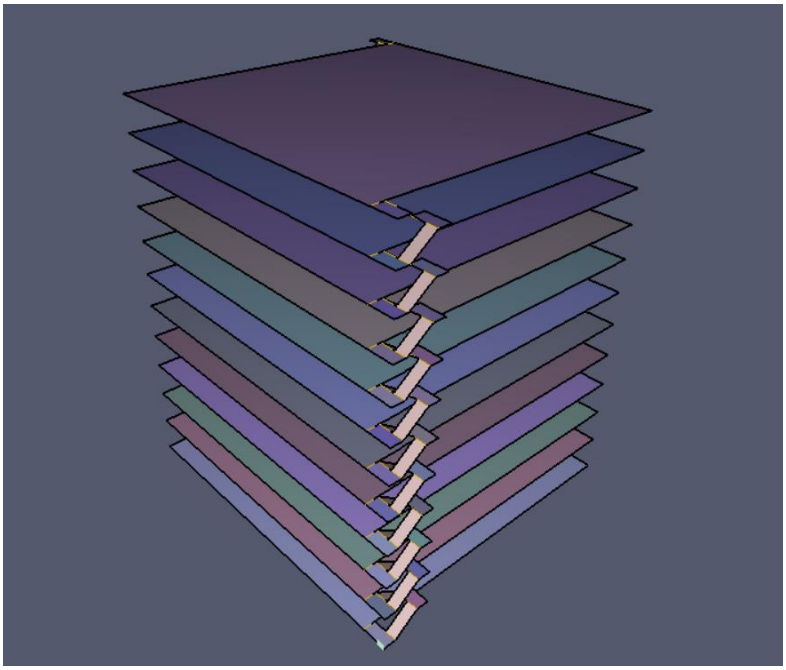

Figure 2: View of egress model with multiple stories.

EGRESS MODELLING RESULTS

Table 4, Figure 3 and Figure 4 display the egress time results for SFPE and Steering modes, respectively. For each simulation mode, the following times are displayed:

1. Total building egress time
2. The maximum time for occupants to clear any one story and enter the exit stair.
3. The mean time for occupants to clear a story and enter the exit stair.

Table 4: Egress modelling results for SFPE and Steering modes. All times are given in seconds.

	SFPE Mode			Steering Mode		
Number of Stories	Total Building Egress Time	Max Time to Clear Story	Mean Time to Clear Story	Total Building Egress Time	Max Time to Clear Story	Mean Time to Clear Story
2	87	76	76	89	72	72
3	162	129	102	152	133	102
4	237	180	144	236	186	141
5	311	227	181	305	220	171
6	387	270	214	354	229	178
7	461	324	233	413	284	195
8	535	375	262	481	305	215
9	613	428	297	554	360	241
10	689	458	314	615	383	257
11	762	525	334	691	424	277
12	838	553	372	762	486	304

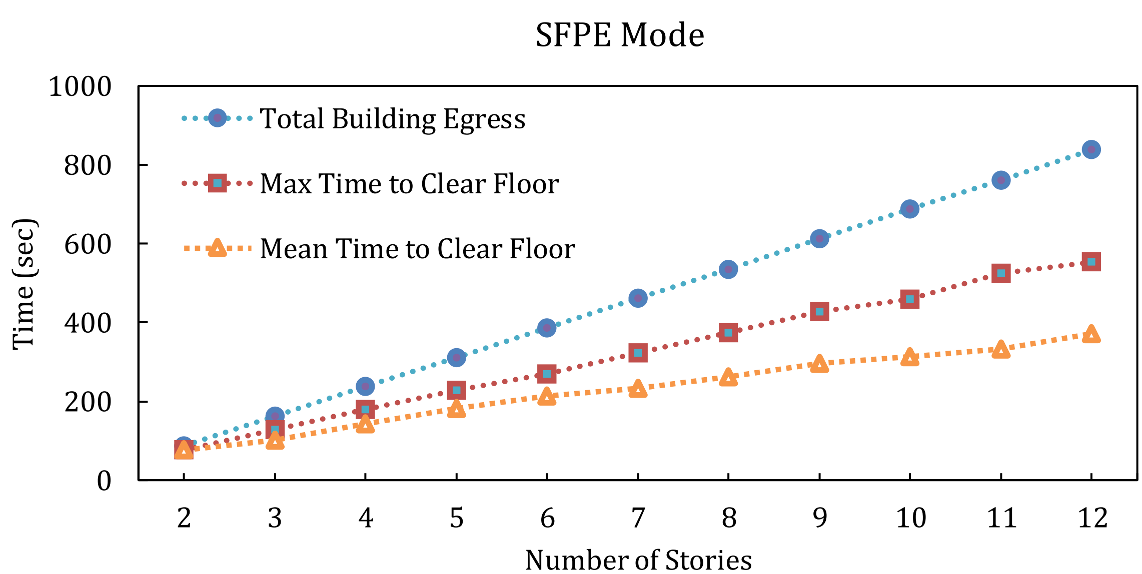

Figure 3: Egress times as a function of number of stories for SFPE mode.

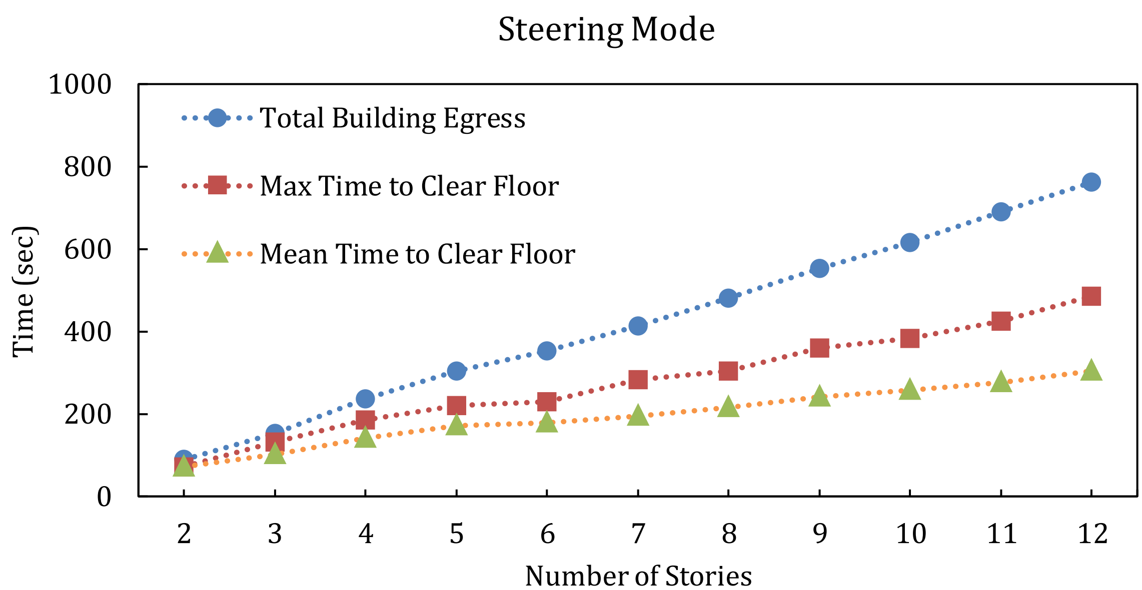

Figure 4: Egress times as a function of number of stories for Steering mode.

In addition to the data presented above, there are important qualitative observations to note. First, there appeared to be an approximately even distribution of occupants between the two exit stairs during the early portions of each simulation. As the simulations continued, Pathfinder's visual model results showed substantial queuing of occupants outside of the entry door to each exit stair. The size of the queues seemed to increase with the number of stories. In the simulations with 10, 11 and 12 stories, the queues were so large that many occupants chose to leave the current queue and walk across the floor and attempt to leave the story through the other exit stair.

Second, there was substantial queuing within the stairwell itself. As these queues developed, the density of occupants on the stair and stair landing increased until occupants could no longer enter the stair enclosure on any given landing. It was at this point that the queue of occupants outside the stair began. Again, the queues appeared to be larger for the simulations with more stories.

Finally, the queues outside of each stairwell door were present on all stories, not just the upper stories. While occupants on Level 2 did not encounter occupants from Level 1 to inhibit their travel to the exit discharge, occupants from the levels above quickly reached the stair and began their descent downward. Once occupants from above reached the Level 2 landing, the queuing within the stair began, ultimately leading to queuing outside the stair door.

DISCUSSION

As expected, the total building egress time was found to be proportional to the number of stories; the more stories that were added to the model, the higher the total egress time. This relationship is logical and does not warrant further analysis. However, the results also show that the maximum and mean times to clear a story are proportional to the number of stories. That means that on average, it takes occupants more time to leave a story and enter an exit stair in taller buildings than for shorter buildings. Similarly, the maximum time for occupants to leave any one story and enter an exit stair is greater for taller buildings than for shorter buildings.

While the qualitative trends found in the modelling results are interesting, the quantitative results are even more definitive. For example, the average time to clear a story for a 12 story building was 372 seconds, substantially longer than the 76 second average for a 2 story building. This time difference of 4 minutes 56 seconds is substantial in evacuation calculations, as building spaces can change from unaffected to untenable in a far shorter amount of time. Occupants finding themselves on “slower” stories were impacted even more, as the maximum time to clear a story for a 12 story building was 553 seconds, a difference of 8 minutes and 1 second above the maximum time for a 2 story building. While this analysis was limited to 12 story buildings, one can easily extrapolate the results for 30, 50 or even 100 story buildings and see that both the mean and maximum times would be substantial for taller buildings.

The results of this analysis show that both the Pathfinder SFPE and Steering modes predict a correlation between the number of stories in a building and the mean and maximum egress times from a story. Considering this analysis in light of the model code requirements discussed previously, a building similar to the egress model used in this study would not require any additional exits or additional egress width until it reached a height of 420 feet above grade level. Assuming a floor height of 12 feet, a building could be up to 35 stories before a 3rd exit stair is required. The proportional relationship found in this analysis means that occupants in such a building would experience substantially longer times to clear any particularly story than occupants in a shorter building.

While this study was limited in scope, the clear relationships predicted by the egress model warrant further study. Future research could involve the study of actual building evacuations to determine if the same trends exist in real human behavior. Additional analysis of egress models should also be conducted to extend the study to taller buildings and buildings with more complex floor geometry. Should additional study and research find the same relationships found here, further discussion and exploration with the code development community is warranted. If such stark differences in egress characteristics exist between short and tall buildings, this data should inform code requirements related to number of exits and egress width.

One potential solution to mitigate the increased queues and egress times observed is to implement a phased or partial evacuation strategy. In a typical partial evacuation strategy, a building fire alarm system notifies occupants only on the story of a reported fire, plus one story above and below. Such a strategy would likely reduce the mean and maximum times to clear a story to a similar time as if the same building had only 3 stories, but further study is needed to verify this hypothesis. Current codes and fire alarm standards in the US and abroad do allow for partial or phased evacuation strategies, however some local jurisdictions do not allow this approach. Additionally, building fire alarm systems must be designed and programmed for partial evacuation, so it may not be possible to pursue this strategy in existing buildings without an update to the fire alarm system.

CONCLUSION

In this simple analysis, an egress model geometry was constructed and evacuation simulations were performed using that geometry replicated in buildings from 2-12 stories. It was found that the mean and maximum times for occupants to clear a story and enter an exit stair are proportional to the number of stories in the building. Current model codes enforced in the United States and many other countries give minimal consideration to the height or number of stories in a building in determining egress requirements. Further exploration involving real evacuation data and additional egress modelling data is warranted and should be considered in the development of future model codes.

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