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Author: James D Amy, Rolf Jensen & Associates

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REDEFINING EGRESS CAPACITY – ALL IN GOOD TIME

JAMES D AMY, JR.
Rolf Jensen & Associates, Inc., Chicago, USA

Abstract

Present day codes require that buildings satisfy egress capacity requirements that have only the most tenuous of connections to egress time. In any emergency, time is a key factor and knowing whether the risk to occupants will exceed an unacceptable threshold prior to the completion of occupant evacuation is critical.

On September 11th, the light occupant load in both structures and the occupant-initiated partial evacuation of WTC 2 prior to the impact of the second plane played a significant role in minimizing the death toll. The time needed for occupants to egress under normal occupant loading was unknown prior to the event, even in light of the bombing in 1993. The death toll, could have been much higher had the attack come in the middle of the workday when movement in the stairways would likely have been slowed by the higher occupant load.

With the development of egress, fire, and other computer based modeling tools, the progress of the fire or other emergency event can be compared to egress of occupants to identify shortcomings of the existing arrangements that would have not otherwise been brought to light. It may not be enough to provide capacity in the form of code complying door, stair, or corridor width. Instead, future designs for certain structures should include analysis of anticipated events and the reaction of the occupants to the events in the form of dual timelines.

This paper will identify limitations of existing capacity requirement calculations, present an example calculation of the timelines of hazard development and occupant egress, and identify structures to which the timed modeling should be applied.

Keywords: World Trade Center, egress, egress time, evacuation, computer modeling

1. Introduction

John J. Fruin's *Pedestrian Planning and Design* was published in 1971. Fruin was one of many researchers who have made an attempt to calculate anticipated flow of people based on the dimensions of their environment. Fruin compared the width of various components used in people movement, corridors, stairs, escalators, sidewalks, etc. with the speed of flow under a range of densities. Fruin compared how the speed with which people moved down a stair varied when there were dozens per minute as compared to hundreds per minute to identify the optimal flow. His objective was to allow designers to set the width of a stair or corridor such that it would be able to handle the load it would carry.

The codes in use in the U.S. make use of factors similar to those developed by Fruin to set minimum widths for egress components. The codes do not make clear the impact of not having the minimum width of a stair or doorway. This is because codes are prescriptive in nature. Building codes also set many other minimum criteria, such as the required fire resistance of structural members and the maximum area or height of a building.

However, there is a growing recognition that building codes have limitations and are directed at structures that are somewhat similar to those studied to develop the code. For example, if a building code sets fire resistance requirements for steel, concrete, and masonry beams or columns, what happens when someone wants to build with a column that is not steel, concrete, or masonry? Either the code must be modified or an interpretation made such that the component constructed of the new material is determined to be equivalent to what was already accepted.

A similar limit can be reached with buildings with respect to occupants exiting the structure. There is some recognition of this in that limits are set for travel distances, in the minimum number of exits, and in the width of egress components. The question, then, is whether those limits capture all that is found in structures being built to satisfy the need for safe egress and whether complete evacuation of a structure should be considered, as well.

2. Egress Design and Criteria

The World Trade Center was attacked on September 11th and the world had the unfortunate opportunity to see the prescriptive approach still embraced by most building codes tested. In many ways, such as the time that the buildings stood before collapsing, the building design passed the test. However, it remains unclear whether the egress design found in the World Trade Center enhanced or hindered egress. There remain questions about the location of stairs and the construction of the stair enclosure. Would concrete masonry unit walls have performed significantly better, allowing more occupants from above the impact floors to escape? Neither location nor construction of the stairs in the World Trade Center would likely have been an issue during a typical emergency. Clearly, the impact of a commercial aircraft on one of the towers was not typical although some non-egress related consideration was given to such an event in the design of the structures.

Putting aside questions about stair construction and location, the question of how long it would have taken to evacuate all occupants from a 110-story building to a safe location during an emergency should have been known prior to the attack. Adequate impetus was provided in 1993 with the bombing of the World Trade Center to address complete evacuation. Many safety improvements were made as a result of that first tragedy, including emergency lighting and photoluminescent pathway marking in the stairs to enhance egress. But the question of how long a total evacuation of the complex would be expected to take was not known, at least not publicly. Evacuation on September 11th, except for the floors above where the planes had hit, was orderly and almost complete prior to collapse. But prior to September 11th, there should have been an answer to the question of how long it was going to take.

The minimum egress design criteria set by the building codes have the objective of enabling occupants to make their way from the vicinity of a fire to a location that is adequately removed from the fire, either by a fire rated barrier or through exiting the building completely and reaching a public way. Once occupants are on the other side of a fire rated barrier or in the public way, they are regarded as having "egressed" even though they may still be inside the building or standing very close to it. Phased evacuation may be undertaken, with the occupants on the floors closest to the fire evacuated first and occupants from other floors evacuated subsequently or even instructed to remain on their floor for the duration of the emergency.

However, other emergency scenarios, as demonstrated on September 11th, may require that all occupants exit the building and move hundreds of feet away prior to being considered safe from the danger posed by the emergency. Phased evacuation may require more time than is available for occupants to exit the building prior to their safety being threatened. Therefore, are the egress requirements in the codes adequate for addressing scenarios, fire or otherwise, that necessitate the removal of all occupants from the building to a remote location?

Having said that, there are some occupancies in which the time necessary for evacuation is considered in the construction requirements. The National Fire Protection Association's *Life Safety Code* (NFPA 101) regards evacuation to be "prompt" if it takes place in 3 minutes or less, "slow" if it takes place in more than 3 minutes but not more than 13 minutes and "impractical" if it requires more than 13 minutes. The evacuation time is directed at occupancies such as health care and detention and correctional facilities where egress may be constrained by occupant mobility or by impediments to egress, including locked doors. It is for this reason that NFPA 101 generally requires fire resistive construction for these facilities.

Additionally, there are many examples of buildings in which computer modeling of egress has been performed. However, that modeling is not the result of code requirements but typically of demand for analysis by architects, engineers, and building and fire department officials concerned with occupant safety.

3. Examples of Egress

The speed of egress varies depending on many factors, including the mobility of occupants, number of occupants, dimension of the egress components, and the distance they must travel. The building codes have allowances for the expected mobility of occupants, requiring that in buildings where occupants may have limitations in mobility such as hospitals, that the width of doors be increased to accommodate persons in wheelchairs and with walkers. Other acknowledgments are made in similar vein to prevent egress from slowing to an unacceptable level. However, that level is somehow tied to a time. Except for the above noted case of setting structural fire resistance requirements based on the evacuation time in several types of occupancies, time is not mentioned in the egress requirements set in building codes. Two simplified examples are provided to demonstrate why this is an issue.

Table 1 – Example Buildings

Item	Building A	Building B
Height (**H**)	35 meters (10 stories)	350 feet (100 stories)
Building Footprint (**L**ength x **W**idth)	60m x 60m	60m x 60m
Square Footage	36,000 square meters	360,000 square meters
Occupants ($\mathbf{n_{occupants}}$)	2,500 (250 per floor)	25,000 (250 per floor)
Stairways	2	4

It is assumed that both buildings are built to meet the building code and that both have a somewhat similar floor layout. Both are assumed to have the same number of occupants per floor. For the initial estimates, walking speeds of 30 meters per minute for horizontal movement ($\mathbf{v_{horizontal}}$) and 7 meters per minute for vertical movement ($\mathbf{v_{vertical}}$) are assumed. No consideration will be given to obstacles or to occupants tiring as they egress although these speeds are conservative for normal occupants in good health. That will be addressed in a second iteration. The below egress time is estimated based on the time to evacuation of a single floor plus the time estimated to descend to grade level plus the time estimated to walk from the building exit to a "safe" distance. The safe distance is not the distance to a public way but the distance beyond which it is expected that an occupant will no longer be in danger from the event at the building. This distance can vary based on the building or the event but is proposed for the purposes of this paper to have some relation to building height. The values used for occupant movement are not based on specific studies or research. They are somewhat arbitrary but not unreasonable and are used for demonstration only. Refined occupant movement speeds might take into account population mobility or population density or integrate assumed notification or pre-movement time.

The egress of occupants in Building A is estimated to take 2 minutes for them to reach the stairways, and 30 seconds to descend each floor. Forty (40) seconds will be assumed necessary for the occupants to reach some distance of safety once they exit the building, assumed to be at least 20 meters, out of the collapse zone or out of the way of emergency personnel. For the last person out, (the last person who leave the 10th floor) in this gross estimation, the time elapsed from the initiation of evacuation was approximately 7 minutes and 40 seconds.

A comparison is made with that figure to Building B. The time estimated for occupants to reach a stair in Building B remains two minutes. Although incorrect, the assumption that descent will average on floor per 30 seconds will remain. The time for occupants to reach a safe distance from the building will increase as the building, being much taller, will have a much larger zone of collapse or occupied by emergency personnel. It will be assumed that persons will need to move at least 200 meters from the building. Large structural debris from the collapse of the World Trade Center struck buildings in excess of 150 meters from their respective bases. The dust clouds and smaller debris spread even further. The time for occupants to cover 200 meters is assumed to be 6 minutes and 40 seconds. The total time for the last occupant from the 100th Floor to reach the safety zone is estimated at almost 59 minutes.

Return to the example but modify it to increase the time that is needed for occupants to descend a floor as they grow more tired with each successive floor. By the time 100-floors have been passed, perhaps the average occupant will be able to descend at a rate of only one floor for each 50 seconds. If the time on average to descend a single floor is 40 seconds when fatigue of occupants is accounted for, that adds more than 16 minutes to overall egress time for the occupants of the 100th Floor. The time to reach safety once outside the building will also increase as the occupants will be fatigued. Assume that an additional 2 minutes will be needed beyond the 6 minutes and 40 seconds previously assumed. The total egress time will now be almost 77 minutes.

Thus, even without other considerations, it is clear that the egress time for a 100-story building is going to be many times that of a 10-story building even though the presumption was that both were designed to meet the building code. A matter of concern is when the time that is needed for egress exceeds the time available for occupants to egress safely. For example, assume that there is a fire on the Second Floor in each of these buildings. Even if it is unlikely, assume that the fire department will be unable to gain control of the fire for one hour. Lastly, assume that just prior to the fire department gaining control, enough smoke has spread into the stair enclosure to prevent occupants from passing the Second Floor and exiting the building. Smoke can spread into a stair when the fire department uses the stair enclosure as an area of refuge from which they attack a fire, opening the door to the fire floor or having the door partially propped open by a fire hose. In Building A, that the stairs being impassible toward the one hour mark is academic as everyone had passed the Second Floor six minutes after the initiation of the evacuation. In Building B, per the calculation, there are still occupants above the Second Floor at 60 minutes.

However, egress is never as simple as in the above examples. Buildings may be designed and even built to meet the building codes but seldom remain in complete compliance. Modifications are sometimes made without consideration to the impact on fire protection. Maintenance is sometimes not performed. This is somewhat unavoidable. Even the fire resistance ratings of walls, ceilings, and structural members will vary from the conditions under which that component was tested. A wall certified as meeting a fire resistance of two hours under test conditions may not last for two hours during an actual fire or may last longer than two hours.

4. Discussion

4.1 Non-Fire Scenarios

What can be done to address the above issue? Increasing the width of doors or number of exits to speed egress does not have an impact when it is the physical act of descending 1,000 feet that requires the most time. There is not any structural modification that can be made to reliably speed egress when fatigue becomes a limiting factor. However, it helps to know that there can be a problem with egress even if the building is fully code compliant.

The collapse of the World Trade Center towers was unexpected at the time it happened. As many as were killed, the death toll could have been far higher if the attack had come at midday when far more employees and visitors would have present. The number trapped above the floors of impact would have been higher and the time to egress for those below the floors of impact would have been greater with the higher occupant density that would have been experienced in the stairs. It is unclear how many in the South Tower, which collapsed after 56 minutes, died only because they did not have enough time to physically leave the building and reach a safe distance from the building. A few had successfully made it through from above the floors of impact but how many were too tired to keep up with the last one out? In the North Tower, collapse took place 100 minutes after impact and still, there were occupants in the building. They were limited to mostly emergency personnel escorting those with more severe physical ailments that had contributed to slow their egress speed. Some of them survived.

Discussions about egress have centered on fire in the past. In the time since September 11th discussions have turned to chemical, biological, and radiological (CBR) attacks as well as bombings. The time that a fire rated barrier may withstand a fire is not important during an attack involving the release of a CBR agent. Instead, the safety of occupants may depend on the time it takes them to egress compared with where the agent will spread and how long it will take to reach various spaces in the building. However, since there is not presently any requirement to analyze the various scenarios that may arise, no baseline exists for evaluating the impact of an event on occupants when time is of the essence.

4.2 Occupant Load and Behavior

Building dimensions in and of themselves are not the only indicator that egress may be of concern. Behind building codes is the understanding that the minimums set have a certain level of risk attached to them. No building code is designed to prevent the possibility of occupant injury or death. There is always some chance that even when a building is code compliant that an occupant may not escape safely from an emergency, sometime based on occupant behavior during the emergency. Thus, the level of risk for the average occupant can be seen to increase as the number of occupants increases. At some point, the number of occupants is great enough that it will trigger the same concern propounded by the building dimensions in the above example. However, determining that threshold is even more difficult as it is not as easily tied to egress time.

4.3 Passing the Threshold

The above example assumed that the initiation of egress coincided with the ignition of the fire. There is more typically some delay in detection of a fire, either by an occupant or by a fire detection system such as a smoke detection system or automatic sprinkler system. Notification of occupants can be further delayed by the time it takes for the fire alarm system, if one is present, to be activated. Even then, observations made from past fires demonstrate that occupant response to an alarm or other form of notification varies. Some begin to egress. Some wait to find friends or relatives before leaving. Others stay to phone the fire department or to finish some task prior to leaving. Still others will not leave until instructed to or forced to by other occupants or fire department personnel. In the case of one occupant of the World Trade Center, fire personnel repeatedly instructed him to leave but eventually had to physically escort him away from his office.

Such behavior is not the norm but proves that occupant response will vary and that the time needed for egress can be lengthened substantially by such occupant actions. Human behavior can be very complicated and some egress models consider dozens of different actions on the part of occupants. The question of when to look at such behavior and the hazards to which occupants may be exposed remains.

It is proposed then that a simple set of parameters can suggest the need for an analysis of egress beyond simply providing egress capacity per the building code. The suggested parameters are shown below but would need to be combined to address a structure where they combine to pass the threshold.

$$\text{Egress Factor} = (\text{tfloor} + \text{tstair} + \text{tperimeter})(\text{noccupant})/1{,}000 \qquad \text{Eq. 1}$$

Where t_{floor} = time to egress floor, calculated as $(L + W)/v_{horizontal}$

t_{stair} = time to descend stairs, calculated as $H/v_{vertical}$

$t_{perimeter}$ = time to reach safe distance from building, calculated as $H/v_{horizontal}$

For Building A, a 10-story building, the Egress Factor is 19. For Building B, the 100-story building, the Egress Factor is 1,450. The threshold where total evacuation time should be analyzed likely falls somewhere between the two. For another type of occupancy, say a large stadium, containing 50,000 persons, the Egress Factor might be 800. While the threshold point bears a great deal of discussion, it is proposed for the above formula to be 100.

Another benefit of this approach is that it does not apply the threshold to buildings based on occupancy types. The safety of 5,000 occupants in an office building is just as important as the safety of 5,000 occupants in an educational or institutional building of similar dimensions.

4.4 Egress Time Calculations on Ships

There is a comparison that can be made between what is proposed above and what is required for cruise ships. The International Maritime Organization (IMO) has required through the International Code Of Safety For High-Speed Craft, adopted in 2000, that the evacuation time for each vessel be less than the time calculated using the formula below.

$$\text{Evacuation Time} = (\text{SFP} - 7)/3 \text{ (minutes)} \qquad \text{Eq. 2}$$

Generally, duration of structural fire protection (SFP) of high hazard spaces is 60 minutes, resulting in a requirement for evacuation in 17 minutes and 40 seconds. The 7 minutes in the formula derives from the assumed time for initial detection and extinguishing action. Division by 3 is included to provide a factor of safety that may be designed to account for weather conditions, time to take the craft from operating speed to full stop, or other factors that may result in delays in evacuation. However, this is a prescriptive requirement; it is applied regardless of the size of high speed craft.

The IMO has also issued "Interim Guidelines for Evacuation Analyses for New and Existing Passenger Ships" a recommended practice which specifies a maximum 60 or 80-minute evacuation time depending on the vessel specifics. The evacuation time includes the time for detection and notification (**A**wareness time), the time for passengers to reach their destination for disembarkation (**T**ravel time) and the time necessary for loading lifeboats (**E**mbarkation time) and launching lifeboats (**L**aunching time). The formula is as shown below:

$$\text{Evacuation Time} = A + T + 2/3(E + L) \qquad \text{Eq. 3}$$

Consider in the above that modern cruise ships may carry 3,500 passengers and 1,500 crew. Evacuating 5,000 persons in 60 minutes from a ship in poor weather conditions can be a severe challenge. However, as with the requirement for high speed craft the requirement for passenger ships is prescriptive in nature. Still, there is recognition that egress time is relevant to passenger safety even though ships may have sprinkler systems or fire rated barriers that allow passengers to remain on the ship in the typical fire scenario.

Conclusions

There are limits to all prescriptive building codes. When these limits are passed, additional measures should be taken to ensure that occupant safety is acceptably addressed. The use of timed egress modeling in conjunction with other modeling to ascertain whether egress time for occupants is likely to be completed prior to the onset of unacceptable conditions is an example of such an additional measure However, since it is unclear as to when the threshold is passed between prescriptive codes being enough and performance based analysis in the form of timed egress analysis in conjunction with fire or other modeling being necessary, a simple calculation is proposed to determine when such analysis may be warranted. This proposed Egress Factor is just a first step taken in the interest of trying to stimulate discussion on the subject of timed egress modeling and the limitations of building codes.

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