EMERGENCY EGRESS STRATEGIES FOR BUILDINGS

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INTRODUCTION

The primary strategy for the safety of building occupants in emergencies (especially fires) is by facilitating their relocation to a safe place. In other than a few institutional occupancies (health care and detentional) this generally involves the use of stairs as part of a protected means of egress (MOE) for vertical evacuation. For tall buildings with large populations, providing sufficient stair capacity for simultaneous egress has been considered impractical by code making organizations, so the strategy of phased evacuation has been employed. To this point in time, little attention has been paid to the special needs of people with disabilities and other (permanent or temporary) physical limitations in moving on stairs.

In the aftermath of September 11, 2001 new attention is being paid to many issues, especially emergency egress from tall buildings. A number of experts have called for a fundamental rethinking of egress strategies including all of the possible components that might be employed. In September 2006 a workshop was organized in Atlanta by CIB W14:Fire and TG50:Tall Buildings, with one of the discussion topics devoted to this issue. This paper is intended to continue that discussion.

PERFORMANCE METRICS FOR EGRESS

In performance design, the usual performance metric for egress systems is that of timed egress analysis. Here a range of calculation methods from simple hand calculations to sophisticated computer simulations that may include behavioral rules of human interaction are used to estimate the Required Safe Egress Time (or RSET). Fire models or calculational methods estimate the time available before escaping occupants are exposed to untenable conditions, Available Safe Egress Time (ASET) and as long as RSET is less than ASET, safety is assumed to be achieved.

A problem is that the design parameter for means of egress in regulation is that of capacity. MOE components are rated by the number of people (total) per unit width. Thus there is no direct connection between regulatory design requirements and the critical performance metric of egress time. A detailed discussion of the basis for egress systems design in regulation can be found in Bukowski and Kuligowski[1].

COMPONENTS OF A MEANS OF EGRESS

A MOE consists of an exit access (normally a common use corridor leading to the exit), the exit itself (normally a stair), and an exit discharge (normally a door to the outside or into a protected corridor leading to the outside). Egress stairs may incorporate areas of rescue assistance which are part of enlarged landings providing space for people (especially with disabilities) to move out of the flow to rest or await assistance. Egress stairs may also incorporate transfer corridors that are used to shift the vertical alignment of the stair horizontally, to go around equipment or to maintain minimum required stair separation at floors where the building floor area changes.

This separation into a horizontal travel component on the originating floor, a vertical component to travel from the originating floor to the level of exit discharge (or other safe location), and a horizontal component to travel to the building perimeter would be common to any egress system. Further, the horizontal components are unlikely to be of a length that an occupant would require more than a few minutes to traverse, so any improvements to them would be unlikely to provide any significant impact on overall performance of the MOE, although their reliability might be improved.

STAIRS

Stairs are the primary means of vertical travel during fire emergencies and are generally effective and reliable, but with several significant shortcomings. Most building regulations require at least two independent stairs so that a single event cannot block access to both. This independence comes from the location of the stairs *remote* from each other. In some locations scissor stairs (two, intertwined stairs in a common shaft) are popular since they minimize the building space required. The disadvantage is that they are not remote and can both be easily compromised by openings in the separating partition. However, when counted as a single stair they provide additional stair capacity in a better configuration than a single, wider stair since there is better access to handrails as people descend.

Another shortcoming of stairs in high rise buildings is that standard firefighting procedures involve the designation of one of the stairs as the attack stair, in which the fire hose is extended to permit its advance onto the fire floor. Once the hose is extended in the stair and charged with water it is nearly impossible for occupants to pass from above. Further, once the door to the fire floor is opened to advance the hose, smoke may enter the stair and contaminate the floors above. Thus it may be necessary to delay firefighting until all occupants clear the stair above the fire floor.

This was observed in the fire in the 52-story Boston Prudential Center on January 2, 1986[2]. The fire began on the 14th floor while the floor was undergoing a tenant fitout with an estimated 1500 occupants in the building. The 14th floor door to stairway B failed early in the fire, permitting smoke and fire to make this stair untenable above the 12th floor. This left only stair A for both occupant egress and fire attack. The fire department could not begin to attack the fire until evacuation was complete – about one hour. The fire severity was somewhat limited by the fact that the fire floor was unfinished and the fuel consisted primarily of stored construction materials. If the fire floor door to stair A had also failed, any remaining occupants above the fire would have been trapped.

A conservative estimate of the time needed for most occupants to descend undamaged and smoke-free egress stairs is about one floor per minute[a]. But a growing proportion of the population has difficulty in traveling on stairs and a small number of people cannot use any stairs without assistance. In general, the number of people who have difficulty with stairs increases with building height. These people include those with obvious mobility

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[a] Reported flow rates down stairs are often in the range of (20 to 30) seconds per floor but can slow as building height increases. Rates of 50 seconds per floor were reported in the 2001 World Trade Center evacuation. Ambiguity of cues, debris in the stairs, or the presence of impaired occupants can slow flows even further. Thus a rule of thumb estimate of one minute per floor is reasonable.

impairments (wheelchair, walker, and crutch users) but increasingly include people with respiratory or cardiac conditions, obesity, and those with temporary conditions ranging from pregnancy to sprains.

Today there are buildings under construction and planned where stairs are impractical for anyone in the upper reaches of a building 250 to 350 floors in height. For stairs used as a means of egress in fires, the record has been very good but not without incident. The most frequent problem is contamination of a stair by smoke due to a door not closed or to (usually pre-existing) breaches in the stair enclosure. Stair enclosures compromised by the initiating event (as was the case at the World Trade Center in both the 1993 and 2001 attacks) are rare, but stair enclosures are only required by regulation to exhibit fire resistance, with no requirements for structural integrity nor impact resistance. Such requirements are only now being considered in response to NIST's WTC recommendations[3]. For example, New York City has adopted a building code requirement[4] for egress stair enclosures to comply with level 2 performance for impact resistance under ASTM C 1629[5].

As mentioned above, any stairs represent significant challenges for some people with disabilities. With some conditions, a person's wheelchair provides critical life support and the person may not survive for long if separated from it. Such chairs are usually quite heavy and difficult for even several people to carry down stairs. Evacuation chairs that can be used to convey many wheelchair users or others with mobility limitations down stairs cannot accommodate these life support devices. These evacuation chairs or even just the physical support of another can allow some people with disabilities to traverse some stairs, but this requires people willing to assist, is fatiguing if the distance traversed is long, and can slow the flow of people in the stair. All these shortcomings need to be considered when determining RSET.

The most detailed studies of flow on stairs were performed by Templar in 1975[6] and influenced the regulatory requirements still in place today. Although Templar found that the current 1100 mm (44 in) minimum stair was "adequate," a 1400 mm (56 in) stair was "preferable." Recently Pauls[7] has challenged the applicability of these to modern society due to the increased trend to obesity and lower stamina. Larger people need more stair width to maintain the same flow, move more slowly, and are capable of traversing fewer flights of stairs before resting. Pauls' hypothesis is supported by recent studies of drills[8] and fire evacuations[9] showing travel speeds down stairs decreasing to a quarter of what was observed in Templar's work. Since the costs to the owner in lost rent over the life of the building for space used by wider stairs can be very high, even significant construction costs of alternate approaches to these problems may be cost effective.

Recently, proposals have been submitted to both US model building code organizations to increase the minimum width of required egress stairs from 1100 mm (44 in) to 1400 mm (56 in) where the stair serves a cumulative occupant load of more than 2000 people[10]. The US General Services Administration estimated that the cost of construction of this wider stair is increased by about 21 %, and that the cost in lost rental of the space occupied by the wider stair is $250 000 to $500 000 per year for a 50 story (2 stairway) office building, depending on geographic location[11].

CORE ARRANGEMENT

Most tall buildings are designed with a core area which contains the elevators, stairs, and shafts in which the utilities run vertically through the building. The core usually serves as the building's spine and often plays a significant role in the structural system. Because the core is most often infrastructure and common use space it is less likely to generate revenue for the owner. The designers spend a great effort to "optimize" the core design, meaning to make it as small as possible, maximizing the revenue producing space on each floor.

The exit access is generally arranged just outside and surrounding the core, with the stairway doors facing outward and cross corridors providing access to elevator lobbies. This exposes the exit access to the exterior of the building, protected only by any partitions that may provide for separation of spaces. In its new 7 World Trade Center[12], the architects (SOM) moved the exit access to the center of the core such that the (reinforced concrete) core protects the access corridor and creates a refuge area on each floor. While this makes the core larger the protected space can shelter the floor occupants from external, natural and man-made hazards with direct access to the stairs and elevators. The cost-benefit of such arrangements needs to be examined.

An aspect of egress system design associated with the arrangement of the core is remoteness. Buildings are required to have at least two, independent exits, separated by a minimum distance; usually not less than one third of the diagonal dimension of the space served. Remoteness is intended to ensure that no single incident can block access to both stairs. Some regulations permit the separation distance to be measured along a walking path between exits, which can allow exits to be adjacent but separated by a perpendicular wall of at least half the required dimension in length. If the initiating event compromises this wall, the remoteness is defeated.

OCCUPANT EGRESS ELEVATORS

Elevators are the normal means of vertical transport in any building taller than a few stories. However during fires, the safety of elevators can be affected by the fire itself and by water from sprinklers and fire hoses, so the policy worldwide is not to use elevators during fires. Elevators are also taken out of service during earthquakes when the lateral acceleration exceeds a level that might compromise further safe operation.

In the 1980's the elevator industry developed Firefighters Emergency Operation (FEO) that is now required in building regulations worldwide. In FEO, detection of smoke in the elevator lobby on any floor or in the machine room results in the elevators being immediately recalled to the designated landing (generally the level of exit discharge) and taken out of service. The responding fire brigade can use a special key to re-activate individual cars to be driven manually by a firefighter. In this mode, hall calls are ignored and the in-car controls operate somewhat differently to provide enhanced safety. Most regulations permit the fire brigade to use elevators being driven by a firefighter to be used to assist people with disabilities in evacuation.

While there are currently no regulations that generally permit occupant egress elevators there are a growing number of systems being approved worldwide under performance-based or alternate solutions provisions. Much of this recent acceptance is associated with an intensive effort in the US by NIST, the American Society of Mechanical Engineers (ASME) and the elevator industry to develop requirements for occupant egress elevators, as documented in a number of publications[13, 14, 15].

The prospect of using the elevators for occupant egress in fires is being enthusiastically embraced by building owners, designers, and regulators for several reasons. First, it permits the location of assembly occupancies (bars, restaurants, and observation decks) on upper floors of tall buildings without the building-code-mandated penalty of larger stairs running the full height of the building to accommodate the occupant load. This is premium space based on the views available from the top. An example is 30 St. Mary Axe in London, which incorporates a bar and restaurant on the top floor and protected elevators running between the assembly space and street level. Second, egress elevators directly address the needs of people with disabilities for self-evacuation. Developers of high-rise condominiums for the elderly see egress elevators as a significant marketing advantage. An example is Petronas Properties in Kuala Lumpur and Marriott Corp. in the US, both of whom are developing high rise condominium properties marketed to older residents. Third, integrating egress elevators into the evacuation procedures of very tall buildings has a very significant impact on total egress times. An example is Taipei 101 where the total evacuation time was reduced from 2 hours to 57 minutes when elevators were incorporated into the evacuation plan[16].

FIRE SERVICE ACCESS ELEVATORS

While fire service access elevators are not a part of the means of egress they do have a significant impact on occupant egress in tall buildings. For any building of sufficient height that egress has not completed before the fire service begins to move into position to begin operations, there is a conflict between occupants leaving and firefighters entering resulting from counterflow in the stairs. NIST studies of the WTC evacuation[9] and of drills in federal buildings[8] indicate that counterflow has little effect on occupant evacuation but significant impact on fire service access, delaying the start of operations and separating firefighting teams. Transferring fire service access to protected elevators eliminates counterflow along with numerous additional advantages to operational efficiency[17].

It should be noted that the use of fire service access elevators does not eliminate the issue of the fire department taking over an attack stairway which is then blocked for occupant use from above by the charged hose. This would still occur because the fire attack would still be made from the stair – however the impact is greatly lessened if the occupants are using elevators for egress or if there are additional stairs.

ELEVATOR EGRESS STRATEGIES

When incorporating elevators into fire evacuation it is important to exploit their strengths while protecting their weaknesses. The typical design metric for elevators in a modern high rise commercial building is to provide sufficient car capacity and speed to be capable of moving 10 % of the total population of the building in 5 minutes during peak times at the start and end of the work day. Thus, any high rise building is able to move its entire population by elevators in one hour or less with the elevators provided for normal use.

Elevators are most efficient when operating in shuttle mode (avoiding time needed for accelerating and decelerating smoothly). Further, it makes sense to use the elevators to move those with the longest distance to go, first. Occupants of lower floors (without disabilities) have a choice to use the stairs. Another consideration is that it is unlikely that any large building will initiate a complete evacuation on an automatic alarm due to the potential for significant business disruption without cause. But there is recent experience with occupants of large buildings initiating a full scale evacuation on their own if they suspect something is wrong in their building. This and other issues are being studied in a survey of high rise building occupants attitudes regarding building evacuation[18].

Thus, an elevator evacuation protocol is likely to begin with an initial alarm summoning the fire department and taking the designated fire service elevator out of service to await fire department arrival at the designated landing. The remaining elevators will go into evacuation mode where they collect occupants of the fire zone (fire floor and two floors above and below) to shuttle them to the level of exit discharge. The elevators would then wait at the designated level for a decision by the incident commander for partial or complete evacuation or for a return to normal service. Waiting at the designated level prevents arriving people from taking the elevators to upper floors during the fire.

A decision for total evacuation would initiate a second phase of the evacuation protocol where the elevators would collect occupants from the highest floors first, shuttling them to the level of exit discharge and returning for another load, working their way down from the top. Hall calls would register people awaiting pickup but would not alter the sequence. People with disabilities would not be given any priority since all occupants are accommodated equally in this system.

Enclosed lobbies on every floor would provide a protected space in which to wait and serve to protect the hoistway from smoke/fire (delaying the initiation of Phase I recall) and from water intrusion from sprinklers or hose streams. Real time signs in every lobby would report system status in real time including how long before cars would arrive to evacuate that floor. The signs at the level of exit discharge would warn not to enter as the elevators are in evacuation mode. Conditions in the lobbies and machine room would be monitored in real time from the incident command. Once staging is completed, the fire service elevator can be used to pick up the injured or stragglers. All of this can be accomplished with commercially available systems.

REFUGE FLOORS

In several Asian countries (China, Singapore) tall buildings must be provided with refuge floors every 20 to 25 floors. These are usually mechanical floors (no normally occupied space) with at least 50 % of the floor area configured as an area of refuge (2-hr separations to equipment spaces, no fuel load, space to hold all occupants of the floors between refuge floors at 0.3 m^2 or 3 ft^2per person). They are required to be open on two opposite sides so that smoke will not accumulate. Refuge floors provide a protected space for occupants to rest or to await assistance, or to cross between stairways[19].

Requirements for refuge floors are relatively new and are currently found in only a few buildings. No real evacuations have occurred but there is some experience from drills that indicates there may be a problem when people reach a refuge floor and decide to wait there rather than continuing the evacuation[20]. Occupants accumulate on the refuge floor such that additional arriving occupants cannot enter. This may be an artifact of a drill where the occupants know they are not in danger and that they will be returning to their floor after the drill. Also, a study using cfd models showed the open sides could permit smoke to enter from an external fire plume originating on a lower floor[21]. Recent revisions require drencher systems on the open sides.

The World Financial Center currently under construction in Shanghai incorporates refuge floors and also utilizes two observation elevators running on the outside of the super columns on diagonal corners of the building. These elevators were originally designed to provide express service only to the observation deck on the top floor. These observation elevators were modified to stop at each of the refuge floors to be used for occupant egress in fires. Thus the furthest an occupant would need to travel in the stairs is 25 floors (13 floors if procedures were to suggest using the closest refuge floor even if it was above your position). Occupants not capable of using the stairs to reach a refuge floor would be picked up by a firefighter driving an interior elevator under FEO.

ACTIVE EVACUATION MANAGEMENT

Increasingly, experts are saying that occupant evacuation proceeding during fire department operations should be actively managed, since those operations can result in risks to occupants due to changing conditions. This was seen in the Cook County office building fire[22] and others where suppression operations make the attack stairway untenable above the fire floor[2]. Such active management involves monitoring in real time to identify conditions that require a modification to the evacuation, and a means to communicate instructions.

Monitoring would likely involve the installation of video cameras in the stairways (one proposal submitted to the ICC in the US is for cameras every five floors). Some concerns have been raised about the workload of monitoring all these cameras. With modern security cameras and software it is unnecessary for a person to monitor the images. The software monitors the image and, as long as there are people moving down the stairs the image is in background. Should there be no people or no movement for a preset time the image is brought forward for the operator. This would allow rapid identification of blockages without undue distraction. These cameras can also identify smoke in the stair which would require redirection of occupants through the voice communication systems already present under current codes.

COMMUNICATION SYSTEMS FOR EGRESS MANAGEMENT

Since the early 20th Century fire alarm systems have been provided in buildings to notify occupants of the need to evacuate. Once the alarm was sounded there was no further need for communication since the action was simply to leave the building as quickly as possible. This changed in the mid-1980's when phased evacuation was introduced for tall buildings where the egress system could not support simultaneous evacuation. It was felt that where occupants were asked to wait for their turn to evacuate, it is necessary to provide a means of making pre-recorded and live, voice messages until the evacuation was complete. This communication was carried out from a fire command center specifically arranged for the fire department to conduct incident command.

New York City adopted Local Law 5-1973 which required voice communication systems for new, high rise (defined as exceeding 100 feet or 30.5 m in height) office buildings and extended this requirement to new mercantile and all high rise hotel occupancies through Local Law 16-1984. In the U.S., the National Fire Protection Association's Technical Committee on Protective Signaling Systems developed NFPA 72F (High Rise Voice Communication Systems, which was published in 1988 and then incorporated as a chapter in the consolidated National Fire Alarm Code, NFPA 72 (1993 and subsequent).

Total evacuation of tall buildings has been a rare event, but as society becomes more risk averse we may find that it occurs more frequently. Also, fire is not the only condition that might trigger a total evacuation. Severe weather, chemical spills, earthquakes, major water leaks, workplace violence, and large-scale power outages are only some of the conditions that have led to building evacuations. In some cases the emergency action is to shelter within the building, which may involve some relocation. The complexity of getting occupants to take the desired action makes an even stronger case for communication systems and proactive evacuation management.

Human factors research clearly shows that people will generally make the right decisions when provided with the (clear and unambiguous) information upon which to base those decisions[23]. Events such as the 1993 and 2001 World Trade Center evacuations as well as evacuations and drills carried out in other tall buildings show the range of things that can go wrong when evacuating large number of people. These all demonstrate the need to actively manage evacuations, including monitoring the process to identify problems, and communications systems to give directions that resolve these problems.

Today, emergency communication systems are common, even in smaller buildings. These initially provide to specific areas (individual floors or fire zones, stairs, and elevators) or to the entire building, pre-recorded or digitally generated voice instructions initially, and the ability for the incident commander to issue live instructions during the incident. Current discussions include the provision of cameras in refuge areas and stairs to provide the incident commander the ability to monitor the evacuation process and to quickly identify problems. To reduce monitoring workload these would be arranged to only display their image if the system detected no people or people not moving in the stairs, or if a call were placed from the location to the command center.
Dynamic signs are being discussed to provide textural information in real time. These could display the time before elevators arrive at a given floor as part of an elevator evacuation system, or to give directions at key points in the egress system on which direction to go. Such dynamic signs have been installed in the new WTC 7 building on the transfer floor, within the egress stairs to instruct occupants on which street exits to use. These signs can display any messages entered from either the fire command or security center of the building.

Another experimental information system developed by the US General Services Administration is a text pager that is issued to any hearing impaired occupant and available to hearing impaired visitors at the security desk. This system can display messages and instructions in real time during any incident and vibrates to get the user’s attention. The only problems noted in technology studies is getting people to carry them and recovering units issued to visitors.

PERFORMANCE GOALS FOR EGRESS SYSTEMS

In its recommendations for changes to codes, standards, and practices resulting from the WTC collapse investigation, NIST recommends that buildings be designed for “timely, complete evacuation.” The point is not that total, simultaneous evacuation will become the norm or will even be common; but it is reasonable to expect that every building will need to be completely evacuated a small number of times over its lifetime. In the recommendations, timely is not defined. Recent experience with the use of elevators for occupant egress in very tall buildings indicates that it is possible to evacuate the entire population of any building of any height within one hour, without any changes to the number, size, or speed of the elevators that would be present if they were not used for evacuation. Thus, the goal of being able to evacuate a building in one hour or less is achievable as an RSET.

In modeling of occupant egress it is recommended that a safety factor of 2 by applied when dealing with the uncertainties of human behavior[24]. In keeping with this conservative approach it is reasonable to double the time available and to require a minimum of 2 h of ASET (available safe egress time) and this is a common requirement today for the fire resistance of the primary structural frame in sprinklered high rise buildings. The result should represent a reasonable and conservative performance goal for complete evacuation (including people with disabilities) within one hour. In addition this permits people with disabilities to self-evacuate with every one else and without the need for assistance or special devices.

CONCLUSIONS

From this discussion it appears obvious that protected elevators will become a primary means of vertical travel in tall buildings. Assuming regulatory agreement with the performance goal of total evacuation in one hour or less, occupant egress elevators would be required in buildings taller than about 50 stories and fire service access elevators in buildings taller than (6 to 9) stories. At the estimated one floor per minute rate, buildings of up to 50 stories can be evacuated in one hour or less using stairs alone. Most fire departments report a preference to use elevators to access fires above the sixth floor. Discussion and consensus is needed on the role of stairs, refuge floors, communication systems, and procedures for egress, relocation, or protection in place in the range of incidents that may be encountered in any building. In some cases, formal threat assessment may be needed to identify scenarios that need to be considered.

Where protected elevators are provided for occupant egress much of the occupant load would be carried by the elevators. Thus there may be less need for wider stairs, and the avoided costs of wider stairs should be more than adequate to cover the additional costs for protecting the elevators and adding monitoring. Owners then would be free to place assembly occupancies high in the buildings without the need for increasing stair capacity. People with disabilities would be afforded the ability to self-evacuate with all other occupants without the need for special arrangements or equipment. In an event where the incident commander decides to require simultaneous evacuation of a building, the entire population should be capable of clearing the building in an hour or less. An hour should be an achievable RSET even for very tall buildings and it should be well within the practical ability of safety designs to provide a protected environment (ASET) of two hours in which to carry out an evacuation including a conservative factor of safety of 2 for variation in human behavior and capability.

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