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High-Rise Building Evacuation Post 911 – Addressing the Issues

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ABSTRACT

The 911 evacuation of the WTC was one of the largest high-rise building evacuations of modern times – requiring the evacuation of some 17,400 people. Many consider the evacuation of the twin towers as a success as 'only' an estimated 2,092 (12%) building occupants failed to escape. However, studies into the evacuation suggest that there were a number of issues which hampered the evacuation including; wayfinding, many occupants did not know where the emergency stairs were located, evacuation of people with reduced mobility (PRM) and the time required to empty the building had the buildings been fully occupied, predicted evacuation times exceeded 2 hours. Here we describe research undertaken by FSEG following 911 to investigate these issues including; the development of a novel emergency signage system, the use of assist devices to aid PRM and the use of lifts for full-building evacuation.

INTRODUCTION

The evacuation of the World Trade Centre (WTC) on 11 September 2001 was one of the largest high-rise building evacuations of modern times – requiring the evacuation of some 17,400 people. As such, the evacuation of the WTC towers is of fundamental importance to the future design of high-rise buildings. The attack on the WTC towers brought home to the world the importance of providing adequate and robust means of evacuation in high-rise buildings.

For many – fire safety professionals and lay people alike - the evacuation performance of the WTC towers on 11 September was considered a success as it has been estimated that of the 17,400 people[1]that may have been within the towers at the time of the attack, 'only' an estimated 2,092 building occupants or 12% of the estimated occupants failed to escape[1]. Of those that failed to escape, it is estimated that 531 (3%) perished on the impact floors[2] and an estimated 1,561 (9%) survived the impact trauma but were unable to evacuate. However studies into the evacuation of the WTC revealed a number of issues impacting evacuation efficiency of the WTC and by implication, other high-rise buildings.

Following 911 several projects were initiated to study the evacuation of the WTC[1,3-5]. The FSEG led project HEED[5,6] – High-rise Evacuation Evaluation Database - was a 3.5 year collaboration between the Universities of Greenwich, Ulster and Liverpool funded by the UK Engineering and Physical Science Research Council (EPSRC - project GR/S74201/01 and EP/D507790). As part of project HEED some 271 evacuees from the twin towers were interviewed generating almost 6,000 pages of transcript and a series of evacuation simulations exploring the evacuation of the North Tower were also conducted[6].

These studies, in particular project HEED, suggested that there were a number of issues which hampered the evacuation including; wayfinding issues: occupants did not know where the emergency stairs were located and had difficulty located them; evacuation of people with reduced mobility (PRM): PRM had difficulty in moving down stairs; evacuation time: the time required to empty the towers had they been fully occupied. This paper will describe research undertaken by FSEG following 911 to investigate these issues including; the development of a novel emergency signage system, the use of assist devices to aid PRM and the use of lifts for full-building evacuation.

WAYFINDING RESEARCH

During the 911 evacuation many of the building occupants were unable to find the emergency stairs, even though they had worked in the building for months. They were unfamiliar with the location of the stairs because they never or rarely made use of them as they always made use of the lifts. However, many people also failed to see the emergency signage pointing to the emergency stairs. The following are three quotations made by survivors of the WTC evacuation derived from the FSEG HEED[5] and BDAG[4] studies into the WTC evacuation:

- **WTC1/025/0002[5] (tower, starting floor, person):**

"…. honestly I didn't know where the evacuation stairwells where….. they say, … look for the exit signs when you go in a place, they really mean that because, y'know unless something's happened before, you're not go to be able to find it".

- **WTC1/057/0002[5]:**

"… we couldn't at that point find the exit. Our stairwell had ended and there were no guide posts to go anywhere….so a number of people started searching for some place to go for another stairwell to go down from the 44th floor. Eventually someone found it so we continued down."

- **WTC1/087[4] (tower, starting floor):**

"…we actually walked past the fire escape, kinda had to turn around and double back until we found the fire escape…"

Following these findings, FSEG embarked on a programme of research to understand how people interact with wayfinding systems such as emergency signage. FSEG conducted a series of experiments to investigate how occupants perceive, interpret and use the information conveyed by standard emergency signage[7,8]. As part of this work they conducted a series of evacuation trials involved participants individually navigating a test area, using a route of their choice[8]. Participants were instructed to evacuate the building in response to the sounding of a fire alarm. The goal that they were set was to evacuate the building as quickly as possible (without running) without staff intervention or further instruction. They could select any route using their judgment unless it appeared to be unavailable (e.g. a door is locked) or if prevented by a member of staff. However, they were not specifically instructed to use the signage system. Indeed, no mention of the signage system was made during the briefing. Participants were then put through the test section individually, and their progress was recorded using a head mounted mini video camera[8].

The results show that only 38% of people 'see' conventional emergency signage in simulated emergency situations in an unfamiliar environment, even if the sign is located directly in front of them and their vision is unobstructed[8]. However, 100% of the people who see the sign follow the sign[8]. These results suggest that current emergency guidance signs are less effective as an aid to wayfinding than they potentially can be. Thus signs are likely to be more effective if their detectability can be improved, while maintaining the comprehensibility of the guidance information they provide. This result could explain why many of the WTC building occupants failed to find the emergency exit routes from their building, even though the building was signed to the regulatory standards.

The results from these trials contributed to the development of the Active Dynamic Signage System (ADSS) concept which was produced into a working prototype by the UK SME Evaclite Ltd (www.evaclite.com). The ADSS is a novel signage design which enhances the signage affordance while maintaining the maximum compliance with existing signage regulations and practice. This design increases the detectability of the signs through the introduction of lit, flashing and running signage component (see Figure 1) to the exiting standard signage design. The conventional static signage system is then turned into a dynamic signage system (DSS), whereas the size of the sign and the format of the signage information remain unchanged. The dynamic nature of the sign (i.e. the flashing cycle) is only activated during an emergency situation, when the alarm is tripped.

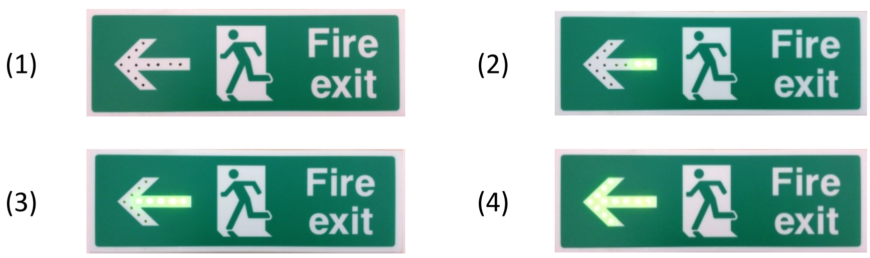


Figure 1: The ADSS showing the flashing arrow indicating a viable exit route.

As part of the EU FP7 GETAWAY project[9], the previously described evacuation trials were repeated using 58 volunteers with the standard emergency signs replaced with the new ADSS concept. The ADSS resembled the standard emergency signs in every respect, including size and mounting location. These trials demonstrated that the use of the ADSS increased the signage detection frequency from 38% to 77%, a 103%

increase in signage detection rate[10]. This demonstrated that the ADSS could be very effective in indicating existing evacuation routes.

In the event of a fire, some exit routes may become non-viable due to the presence of fire or smoke. In terrorist situations, such as in the Nariboi shopping mall incident, certain regions may become hazardous due to the presence of the terrorists. In these cases it is important to identify routes which are no longer considered to be safe or viable. If the exit route indicated by the sign is considered to be non-viable, a large red cross is activated which runs across the face of the sign. The majority of red LEDS in the cross are static and, once the sign is activated remain on throughout the evacuation. However, the first and last two LEDS in the cross on the left and right side flash alternatively, drawing attention to the sign (see Figure 2).

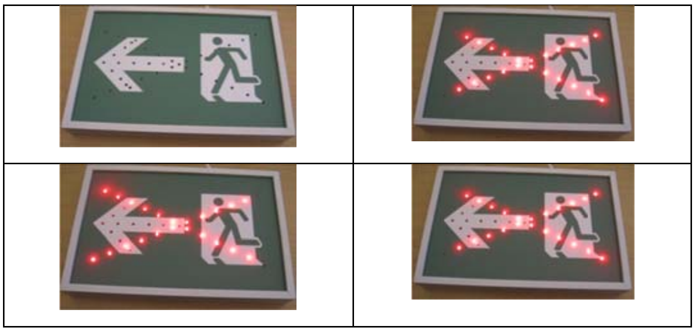


Figure 2: The ADSS showing the flashing red cross indicating a negated route.

To test the comprehensibility of the negated sign concept an international web based survey was undertaken. The survey involved four possible designs of negated sign in order to determine which sign, if any, conveyed the clearest indication that the exit route originally indicated by the sign was no longer considered viable. In total 451 people responded to the survey from more than 10 countries. The option adopted in Figure 2 proved to be the best understood, with a 93% comprehension rate.

The FSEG concept to improve wayfinding systems makes use of ADSS which attract people to the emergency sign and so increases the likelihood that they will find a route to an exit. Furthermore, through information from the fire detection system, CCTV system and the use of faster than real time computer evacuation simulation performed using the buildingEXODUS software[6] the system can be made Intelligent, and identify the optimal evacuation route for building occupants, thereby creating an Intelligent Active Dynamic System (IADSS). In this way the IADSS increases the population's awareness of viable exit routes reducing the number of casualties.

EVACUATION ASSIST DEVICES

A large number of PRM were in the WTC on 911. Their evacuation was made more difficult by their disabilities and the lack of suitable means of assistance. While a number of PRM managed to safely evacuate with the aid of others, a significant number of PRM failed to safely evacuate. The following is an example of a PRM survivor of the WTC evacuation derived from the FSEG HEED[5] study:

- **WTC1/020/0001[5]:** Female, located on 20th floor. She had knee surgery and severe arthritis, could only walk short distances and used a scooter for longer distances.

Participant: "(We) took up the whole stairway"
Interviewer: " How fast were you going down the stairs"
Participant: ".....I (was) doing step-step-step [staccato time]"
Interviewer: "Would you put both feet on one step?"
Participant: "Yeah, on one step".
Participant: "Yeah, one cane in my left hand and I held onto the right-hand stairbar…"
Interviewer: "Did you stop to take a rest"
Participant: "Well yeah. …we would go over to the corner on the landing ….. So people could then go around us. So we would do every second landing just about"
Participant: "So when we would sense there was a [person who wanted to pass], we'd just get into our little tuck position in the corner of the stairwell and let them go."

The PRM required three helpers to assist her down the stairs on 911. With her helpers, the PRM took up the entire width of the stair. Their descent was quite slow and they made it difficult for others to pass them on the stairs. A range of devices are available to assist in the evacuation of PRM down stairs. Four common types of movement assist devices are: stretcher, carry chair, evacuation chair and rescue sheet (see Figure 3). However there are a number of important operational issues concerning the use of these devices, such as; how easy are these devices to use, how quickly can they descend stairs and how easy is it for other stair users to pass these devices? While these devices have been in use for some time around the world, little or no quantification of their capabilities had been undertaken.

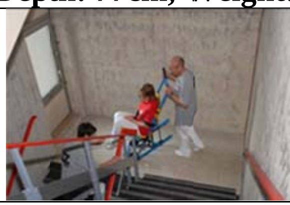
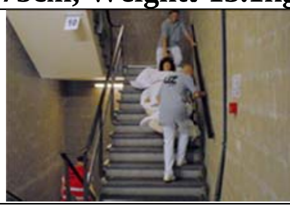
Stretcher: Length: 120cm, Width: 43cm, Weight: 8.9kg	**Evacuation Chair: Height: 138cm, Width: 52cm, Depth: 77cm, Weight: 10.6kg**
	
Carry Chair: Height: 95cm, Width: 48cm, Depth: 61cm, Weight: 7.1kg	**Rescue Sheet: Length: 200cm, Width: 75cm, Weight: 13.1kg**
	

Figure 3: Assist devices used in trials.

To determine their operational capabilities FSEG undertook a series of trials using staff trained in the use of each of the devices to measure the performance capabilities of the various devices. Trained staff were used as this work was intended to determine the innate capabilities of the devices not the impact of staff training. A series of 32 trials were undertaken at the Ghent University Hospital using male and female assist teams carrying a PRM down 11 floors using each of the devices[11]. The trials were used to address the following issues[12]:

- Preparation Time - the time required for manual handling teams to secure a PRM from a wheelchair into each device.
- Horizontal Speeds – how quickly each device travelled along a corridor with hard vinyl flooring and for opening various types of doors while operating the device.
- Vertical Speeds – how quickly each device descended the emergency stairs, including speed per floor and an analysis of rest breaks that the operating teams took while traversing the stairs.
- Overtaking Potential – the ease at which other building occupants can evacuate alongside each device, including the space taken up on while turning on landing, the number of lanes occupied by the device on stairs and the overtaking experience of participants.

A detailed set of results from these trials may be found in[12]. The results demonstrated that in horizontal transportation the devices with wheels, i.e. the evacuation chair and carry chair, are the fastest, with average speeds of 1.5 m/s, comparable to the average free walking speed quoted by Fruin of 1.4 m/s[13]. The rescue sheet is the slowest device with an average speed of 0.9 m/s. In vertical movement, the results indicate that the evacuation chair is the fastest device, averaging 0.83 m/s while the stretcher is the slowest device, averaging 0.53 m/s.

Fatigue does not appear to be an issue in the vertical descent speed of any of the devices however; the devices stopped frequently during the stair descent, with only the evacuation chair not stopping once during this phase. The devices with the best overtaking potential for other stair users was the evacuation chair as it only blocked one lane on the stair; the stretcher was the worst as it blocked the entire stair. The carry chair was similar to the stretcher when operated by female handlers and similar to the evacuation chair when operated by male handlers.

The number of operators required to utilise the device is also of great importance, especially in situations where there may be many PRM or in situations where there are few trained device handlers. The evacuation chair was the best device in this respect, only requiring a single handler for both horizontal and vertical movement, while the other devices required two or four handlers. Ideally, the device performance should be gender independent, with the same performance being achieved by male and female handlers. In horizontal movement, the carry chair had the smallest difference in gender performance (5.1%) while the rescue sheet had the greatest difference (38%). In vertical movement, the evacuation chair had the smallest difference (1.2%) while the rescue sheet had the greatest (37%); however, the carry chair utilised an additional female handler.

The data collected from these trials have been used to develop simple performance metric to assist building managers determine which is the most appropriate device for their particular situation[12]. Furthermore, the data has been incorporated into the buildingEXODUS software[6] to enable realistic evacuation simulations to be performed of evacuations of PRM utilising these devices. This work is being extended to include detailed models of each of the assist devices within the software modelling environment.

USING LIFTS FOR EVACUATION

As part of project HEED a detailed analysis of the evacuation of WTC1 was undertaken using the buildingEXODUS evacuation simulation software[6]. In attempting to simulate the events of 11 September 2001, the geometry of WTC1 was implemented within the software. The model assumes that there is no significant damage to the building below the impact zone and that the elevators are not available to assist in the evacuation. The geometry is considered to be a good representation of the actual building, being based on detailed architect plans. The broad structure of the building geometry represented within the software included the number and width of staircases, number of floors, number of unoccupied floors, layout of staircase geometry, widths of main doors, etc. Within the model the population was distributed only on the rented floors. In total two different sized populations consisting of 9,650 and 25,500 people were considered.

The 9,650 population case is intended to represent the maximum number of people thought to have been in WTC1 at the time of the attack. From the NIST estimates it is thought that 1,462 people in WTC1 died, this included essentially everyone that was above the 91st floor (i.e. floors 92-110) and a few people on the lower levels[1], resulting in 8,188 survivors able to evacuate from WTC1. The simulations assume that the population is distributed evenly amongst the remaining 77 occupied floors producing an average number of 107 people per occupied floor and a total of 8,239 people within the entire simulation able to evacuate. Another population distribution considered in this analysis is intended to represent the maximum building occupancy. This consists of 25,500 building occupants and visitors[1]. Taken across the 93 occupied floors this produces a load factor of 274.2 people per floor. Using a load factor of 274 people per floor produces a total building population of 25,482 across all the occupied floors. The population below the impact floors and thus able to evacuate in this case consists of 21,098 people. The remaining 4,384 are assumed to be either impact victims or trapped above the impact floors.

The model predicts the total evacuation time of the building for 8,239 survivors – the maximum likely building population - to be approximately ***1 hour 27 minutes +/- 2 minutes***, depending on the precise nature of the model assumptions. This time compares favourably with the observation that the building collapsed after some ***1 hour 42 minutes*** and supports the view that everyone that was able to escape from WTC1 on the day of the incident probably did manage to do so.

But how would the evacuation have progressed if the normal working occupancy of approximately 25,500 people occupied each building? Using the idealised assumptions of this study (relating to for example the population distribution and the response time distribution), the predicted time required to evacuate the building is estimated to be approximately ***2 hours 18 minutes***[6]. This implies that at the time of WTC1 collapse, the expected death toll would be 7,492, with some 3,108 people caught on the stairs and 4,384 people either killed in the impact or caught above the 91st floor. The results suggest that a mass evacuation of the fully occupied building in a 911 scenario would lead to extremely heavy congestion on the stairs leading to a highly inefficient evacuation, resulting in a high expected loss of life.

The realisation that it is not possible to safely evacuate a fully occupied high-rise building by stairs alone has led to the development of the concept of using lifts for evacuation. This approach is being used in countries around the world, including the UK, Australia and the USA. However, an assumption often made by fire engineers is that if lifts are available for evacuation, and the population are aware that it is safe to use lifts for evacuation, they will make use of the lifts. This is a dangerous assumption to make as it assumes that the population will be compliant and perform in the idealised way that the fire engineers would like, thus providing an over optimistic assessment of the efficiency to be gained from the use of lifts for evacuation. Previous studies, based on this simplistic assumption suggest that the combined use of lifts and stairs can speed-up full building evacuation by as much as 50% compared to the use of stairs alone[14-17]. However, in these modelling examples ideal "compliant" occupant behaviour was assumed. This usually means that all the agents that were designated to use the lifts waited to use the lifts for as long as required without consideration to the local time evolving conditions. However, how many people would actually consider using a lift rather than the stairs in an emergency? How long would people wait for a lift? How would people react to local conditions? The following is an example of a female survivor of the WTC evacuation derived from the FSEG HEED[5] study:

- **WTC1/077/0001:** Person started on the 77 floor and was in charge of group of people.

> "Let me add too that, at the 44th floor there was what they call an inter-zone elevator bank, we were led off the stairwell at the 44th floor and shown to that elevator where there are hundreds of people milling and I looked at that and I turned around to my team and I said 'no, I am not waiting for an elevator in a building on fire. Let's go' and I walked back to the stairwell and they did too and then we proceeded down"

Under what conditions will people wait for the lift? Would people in different countries behave differently? Answers to these questions are essential if engineers are to understand how lifts are likely to be used in an emergency situation, develop realistic computer models that predict building evacuation using lifts and design reliable evacuation systems in which both stairs and lifts are used. To address these questions FSEG developed an online survey asking participants how they would behave with regards to lift/stair usage within a series of hypothetical situations[18].

The use of a publically accessible online survey was intended to reach as wide an international audience as possible coming from a broad variety of different cultural backgrounds. In total 468 participants completed the survey, of which 424 provided complete main demographic information. Of all participants 60.6% (269) were male and 39.4% (175) were female. Of all participants who provided age data (N=444), the average age was 35.0 year. Of all the participants, 63.5% confirmed that their place of work possessed lifts with these buildings varying from 2 to 78 floors with an average of 10.1 floors, with over half (54.9%) of those buildings being over 5 floors in height. Approximately 15.6% of all participants had at least one lift in their place of residence, varying from 3 to 35 floors with an average of 10.8 floors in height, with approximately three quarters (75.3%) of those buildings being greater than 5 floors in height. Whilst overall participants came from some 23 different countries, six countries made up approximately 88.9% of all participants: UK (30.8%), China (25.9%), US (12.8%), Germany (11.1%), Japan (5.6%), Australia (2.8%).

Despite being informed that the lifts were a safe and acceptable option, two thirds of the sample (308) said they would not consider using a lift to evacuate. This suggests that caution must be taken when designing evacuation systems for buildings that utilise lifts. It is suggested that simply providing signage that indicates it is safe to utilise the lift in an evacuation will not be sufficient to convince occupants to use the lifts for evacuation. A significant difference was noted between the number of participants that would consider using a lift during an evacuation according to country; with almost twice the proportion of US participants (approx. 1 in 2 (52.5%)) considering using a lift during evacuation compared to the proportion of Chinese participants (approx. 1 in 5 (21.5%)). This suggests that there are potentially cultural differences with regards to the acceptance of using lifts during evacuations.

Of the participants whom would consider using a lift (152), less than 10% said that they would always use a lift, while over 75% (121) said that the height of the floor they were on would influence their decision to use a lift. The height of the building was also a significant factor in determining whether or not they would use the lift. As the floor height increases the proportion of participants that would consider using the lift increases. Approximately 10% of the population would use a lift even if located below the 10th floor. The proportion of the population that would use the lift increases to approximately 80% up to floor 40 and remains at this level even for higher floors. This suggests that approximately 20% of the population will not use a lift to evacuate irrespective of floor height. A very small proportion of participants stated that they would wait in a lift waiting area regardless of crowd density and/or would wait for "as long as it takes" for a lift to service their floor. However, the majority of participants indicated there was a critical level of crowd density in the lift waiting area which, if reached or exceeded, they would redirect to the stairs. Furthermore, this critical density appears to increase as the floor height increases; reflecting the decreased attractiveness of using the stairs on progressively higher floors. The majority of participants also specified a finite time they would be prepared to wait for a lift; while this was dependent on floor height (the higher the floor, the longer the acceptable wait time), less than 10% of participants were prepared to wait more than 15 minutes regardless of floor height (see Figure 5). These results clearly show that in evacuation situations, building occupants are prepared to utilise lifts for evacuation but that this is strongly dependent on floor height, crowd density and expected lift wait time. The results suggest that people adapt their behaviour according to changing local conditions.

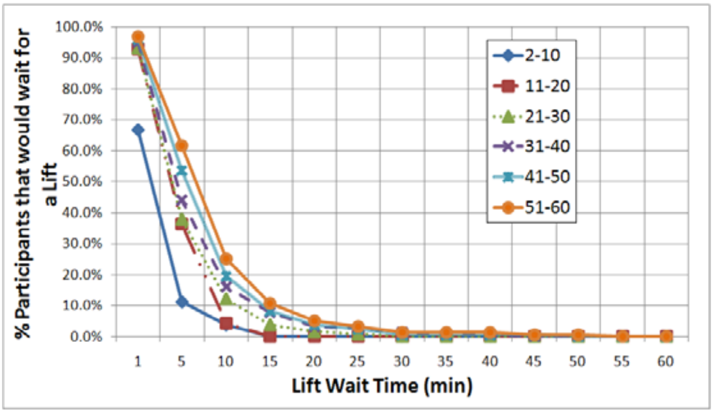


Figure 4: Cumulative proportion of participants that would wait for a lift as a function of wait time (grouped into 5 min intervals) for each floor range.

It is essential that such behaviour is represented within evacuation simulation models if representative and meaningful predictions of lift evacuation are to be achieved. The human behaviour data generated from this study has been incorporated into the buildingEXODUS evacuation simulation software and used to evaluate building evacuation scenarios using lifts[19].

The agent-lift model within buildingEXODUS V6.0 involves three core agent behaviours: lift bank selection; lift waiting area selection and wait duration; and lift car selection and entry[19]. The lift bank/stair selection system allows a user to specify the probability that an agent will use a lift/stair according to the floor an agent is on. Of agents that choose to use a lift, when those agent's enter into a lift waiting area they assess the levels of congestion in the lift waiting area and decide if they will redirect to the nearest stairs. To perform this task all agents that initially choose to use a lift are assigned a congestion threshold value. At any time whilst the agent is in the lift waiting area, if the levels of congestion exceed the agents congestion threshold the agent will decide whether to continue to wait for a lift or redirect to the stairs. This decision is based on a probability determined by the time the agent has already spent waiting in the lift waiting area divided by the total evacuation time. This means that agents who have waited in the lift waiting area for a longer period of time will have an increased chance of maintaining their initial choice to use the lift if their congestion threshold is reached or exceeded. Agents whose congestion threshold is reached or exceeded immediately upon entering the lift waiting area will have an increased probability of redirecting to the stairs; representing a decreased level of commitment to their initial choice.

Of the agents that decide not to redirect to the stairs due to congestion, initially choose a location to wait and also a length of time that they are prepared to wait in the lift waiting area. If the agent has not boarded a lift by the time their lift wait time has expired they will redirect to the stairs. Irrespective of an agent redirecting to the stairs either due to congestion or lift wait time expiration, providing the agent is still inside the lift waiting area they are still able to board a lift should one become available. This allows agents that have redirected to the stairs but still inside the lift waiting area to board a lift should it become available i.e. they will not walk past an open lift if they are able to board it. All the data used within buildingEXODUS related to agent lift behaviour is derived from the FSEG international survey[18].

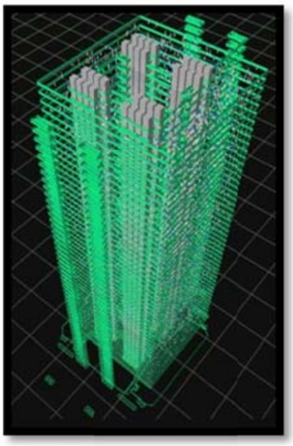
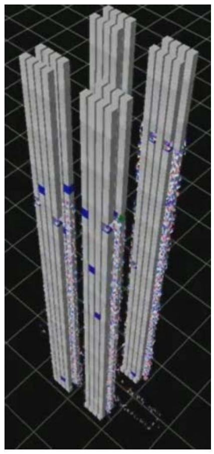
	
Building core, lift and stair shafts	**Lifts are at different levels with agents gathering in lift lobbies.**

Figure 5: buildingEXODUS images of 50 floor high-rise building lift evacuation

Using the buildingEXODUS lift model, a series of 11 evacuation scenarios involving different lift dispatch strategies were investigated involving a hypothetical 50 floor building consisting of; four staircases and up to four lift banks, each with eight lifts and a building population of 7,840 agents. The main findings from this study include:

- Comparisons with identical scenarios where agents exhibited compliant/homogenous behaviour suggest that lift human factors can considerably decrease the efficiency of an evacuation lift dispatch strategy. The extent to which this occurs is dependent on the lift dispatch strategy employed.
- In all scenarios examined the lifts were underutilised with most agents electing to use the stairs. This reflects occupant reservations about using a lift, waiting in large crowds or waiting for a given period of time for a lift.
- Results suggest the most efficient and fastest lift evacuation strategy was where multiple sky lobbies were used and agents travelled down the stairs to their nearest sky lobby. This strategy staggered the arrival of agents to the lift lobbies which subsequently decreased the levels of congestion in the lift waiting areas and decreased the average time waiting for a lift.
- Past studies have shown that using a combination of lifts and stairs has the potential to decrease total evacuation time by as much as 50% compared to stair only scenarios[14-17]. The FSEG study suggests that this is over-optimistic. With consideration to adaptive human factors based on the analysis of empirical data, it is suggested that a decrease in total evacuation time of up to a 33% has been found to be achievable. This is due to the underutilisation of the lift system reflecting occupant reservations about using lifts during an evacuation. With increased occupant training and awareness of evacuation lift usage procedure it is postulated that this could increase the number of lift users

during an evacuation. Subsequently this would likely increase lift utilisation and general lift evacuation efficiency. The extent to which this may occur requires further investigation.

The WTC evacuation analysis was reassessed using the buildingEXODUS lift model. The question that was addressed was, could the full building population (25,500) be evacuated using the available lifts. Unfortunately, detailed information concerning the WTC lift capabilities was not available and so reasonable approximations concerning the lift capabilities were made (see Table 1 and Table 2).

Table 1: Assumed lift parameter for WTC evacuation simulation

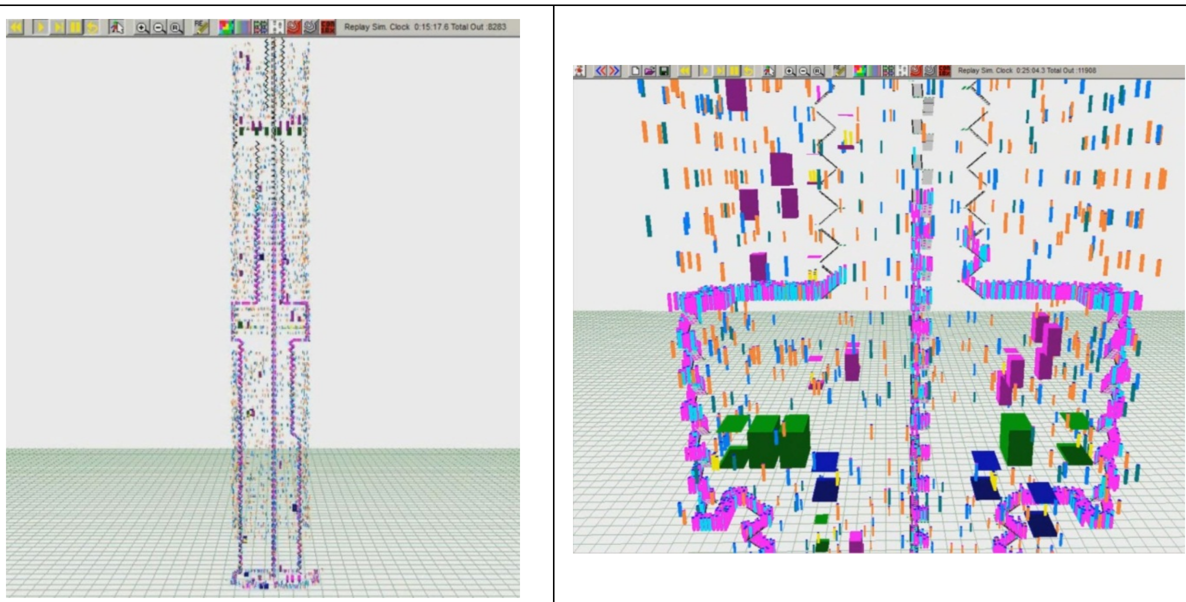
	Capacity	Max Speed	Acceleration	Deceleration
Express Lifts (from Sky Lobbies)	55	8.1 m/s	1.2 m/s^2	1.2 m/s^2
Local Lifts	12	4.0 m/s	1.1 m/s^2	1.1 m/s^2

Two lift scenarios were considered. In Scenario 1 all agents attempt to evacuate using their nearest lift bank. All agents will wait until the lift arrives and will not attempt to use the stairs to evacuate. All floors on which agents are initially located are directly serviced by lifts except floors 43 and 77. Agents on these floors were forced to ascend one floor via the stairs to the Sky Lobby directly above them from where they could use the lifts. In Scenario 2 the agent behaviour is as described above and is based on the data collected in the survey. In this case, ***ALL*** agents will consider using a lift, but some may change their minds based on wait time and or congestion. So this case while more realistic than Scenario 1 is optimistic in that all agents will at least consider using lifts.

Table 2: Number, type and sequencing of lifts for WTC evacuation application

Pick up floors	Drop off floor	Start floor	Lift type	# Lifts
87-91	78	78	Local	6
79-86	78	78	Local	6
78	1	1	Express	12
67-74	44	44	Local	6
61-66	44	44	Local	6
54-60	44	44	Local	6
45-53	44	44	Local	6
44	1	1	Express	8
33-40	1	1	Local	6
25-32	1	1	Local	6
17-24	1	1	Local	6
9-16	1	1	Local	6

The evacuation times for the lift scenarios are based on the average results for 50 simulations. The population distribution and population parameters are identical to those used in the earlier evacuation using simulations using stairs only. As reported earlier, with a normal occupancy of approximately 25,500 people it is estimated that it would have required approximately ***2 hours 18 minutes***[6] to evacuate the entire building by stairs alone, resulting in an estimated 7,492 fatalities. Had the lifts been used for a full building evacuation, assuming that all the population made use of the lifts, the building could have been evacuated in an average of ***1 hour 10 minutes*** assuming that everyone used the lifts, and ***1 hour 23 minutes*** (see Figure 6). Thus in both cases it would have been possible for those occupants located below the impact floors to safely evacuate the fully occupied building. In Scenario 2 where occupants had a choice whether to use stairs or lifts, but everyone initially opted to use the lifts, 58% of the population evacuated using stairs alone (they gave up waiting for the lifts or they were deterred by the number of people waiting for the lifts), 39% utilised only lifts to evacuate and 3% utilised a combination of stairs and lifts. In Scenario 1 there were a total of 32,736 lift journeys while in Scenario 2 there were 14,356 lift journeys.



View of full building evacuation	Close up showing express lifts, local lifts and stairs

Figure 6: buildingEXODUS simulation of WTC lift evacuation scenario

CONCLUSIONS

Studies of the WTC evacuation suggest that there were a number of issues which hampered the evacuation including; wayfinding, evacuation of PRM and the time required to empty the building had the buildings been fully occupied. FSEG research post 911 has focused on these issues with the aim of better understanding them and if possible, finding ways that they can be addressed. To address the issue of wayfinding in high-rise buildings and other complex buildings, FSEG have developed the concept of Intelligent Active Dynamic Signage Systems which improve the affordance of standard emergency exit signs through the introduction of flashing LEDs. The system is made “intelligent” through the use of faster than real time evacuation simulation provided by the buildingEXODUS software linked to CCTV data identifying the location of the population and fire detection information indicating the location of fire hazards. The evacuation of PRM from multi-floor buildings has been addressed by a study of the effectiveness of assist devices used to carry PRM down stairs. The work has quantified the performance capabilities of four commonly used devices enabling building managers to better select devices for their particular applications. The data is also being incorporated within the buildingEXODUS software to enable the modelling of the various devices in building applications. Finally, the use of lifts for evacuation has been explored through the collection of human behaviour data relating to factors that influence the use of lifts for evacuation. This data has been implemented within the buildingEXODUS lift model allowing the simulation of realistic human behaviour in evacuations incorporating lifts. Incorporating human behaviour into the use of lifts for evacuation reduces the efficiency of lift evacuation scenarios however, lifts are still capable of significantly reducing the time required to evacuate high-rise buildings compared to stairs alone. In simulations incorporating appropriate human behaviour, it was demonstrated that it could have been possible to evacuate the fully occupied North Tower of the WTC using a combination of lifts and stairs prior to the towers collapse. Considerably more effort is still required in all of these areas to ensure the safety of all those who live and work in high-rise buildings around the world.

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