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SPECIAL ISSUE PAPER

The UK WTC 9/11 evacuation study: An overview of findings derived from first-hand interview data and computer modelling

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SUMMARY

This paper briefly describes the methodologies employed in the collection and storage of first-hand accounts of evacuation experiences derived from face-to-face interviews with evacuees from the World Trade Centre (WTC) Twin Towers complex on 11 September 2001 and the development of the High-rise Evacuation Evaluation Database (HEED). The main focus of the paper is to present an overview of the preliminary analysis of data derived from the evacuation of the North Tower with an emphasis on frequency of occupant stoppages on stairs, occupant stair travel speeds and occupant response times. The paper also describes some of the evacuation modelling analyses of the evacuation of the North Tower undertaken as part of project HEED. Copyright © 2011 John Wiley & Sons, Ltd.

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INTRODUCTION

The evacuation of the WTC complex on 9/11 is one of the largest full-scale evacuations of people in modern times with over 14 000 people escaping from the buildings. The survivors' evacuation experiences provide valuable insights into the factors that helped and hindered egress within the rapidly changing high-rise building environment. Thus, understanding survivors' evacuation experiences is a vital component in unravelling the complex inter-related processes that drive high-rise building evacuation. Following 9/11 several projects were initiated around the world to study the evacuation of the WTC [1–3]. Project HEED [4–13]—High-rise Evacuation Evaluation Database—was a 3.5-year collaboration between the Universities of Greenwich (led by Prof. Ed Galea who was also the project principal investigator, with team members, Ms Rachel Day, Dr Lynn Hulse, Mr Gary Sharp and Mr Asim Siddiqui), Ulster (led by Prof. Jim Shields, with team members Dr Karen Boyce and Ms Louise Summerfield) and Liverpool (led by Prof. David Canter, with team members Ms Melissa Marselle and Mr Paul Greenall) 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 6000 pages of transcript. While analysis of the data collected by project HEED is still underway, both by HEED project partners and independently by other researchers from around the world, including NIST in the U.S.A., thus far the HEED team have produced 13 journal papers and

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conference presentations describing this work [4–13]. A full list of publications, including PDF versions of the publications can be found on the project web site at: http://fseg2.gre.ac.uk/HEED/. The main accomplishments of project HEED to date include:

- Developing and implementing an interview protocol capable of capturing the behavioural experiences of those who evacuated from the WTC twin towers [4–8].
- Developing an interactive online relational database (the HEED database) of the evacuees' experiences which includes full interview transcripts, allowing bona fide researchers and code officials' access to the collected information [4–8].
- Undertaking preliminary analysis of the collected information to identify and quantify some of the key issues that influence building evacuation [7, 10, 11].
- Undertaking detailed analysis of the evacuation of the North Tower of the WTC through advanced computer simulation and using these findings to comment on the viability of full building evacuation by stairs [9, 10].
- The identification of the current strengths and weaknesses in evacuation modelling technology and providing a basis for developing improved behavioural algorithms for high-rise building evacuation models [9–11].

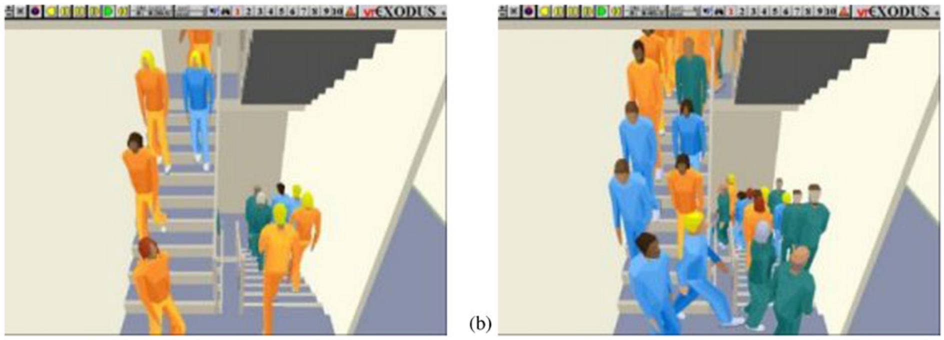
The main features that distinguish project HEED from other WTC projects are:

- A more open approach to data collection through the development of an interview process that attempts to extract a richness of data not previously evident in other projects.
- An attempt to understand more fully the social and organizational factors that influence the evacuation activity, e.g. the influence of groups, organizational structure and perception of risk.
- An attempt to quantify crowd densities and understand how these contributed to the observed behaviour and human performance.
- Accessibility of the data, and full interview transcripts (almost 6000 pages), through the development of an online relational database which is accessible by *bona fide* users. For example, amongst current organizations that have access to the HEED database is NIST.
- Detailed evacuation modelling analysis investigating a number of issues concerning the evacuation of the North Tower.

This paper provides an overview of the methodologies developed for project HEED and a summary of some of the data analysis and computer modelling analysis conducted by the FSEG HEED project team. A more detailed account of the research protocols can be found in [4], whereas a more detailed account of the computer modelling can be found in [9].

RESEARCH PROTOCOLS

The HEED project focused on those persons who evacuated from WTC1 or WTC2 on 9/11. Participants for the interviews were recruited mainly from the World Trade Centre Health Registry (WTCHR), compiled by the NYC DOHMH. Individuals who wished to take part in the study were invited to register on the project's web-site and invited to complete a web-based Pre-Interview Questionnaire. In total, 3064 invitation letters were sent via the DOHMH. A 9.3% response rate was obtained from the DOHMH mailshot and 287 people registered to take part in our study. In total 271 interviews were conducted during five extended interview periods by the researchers in New York. The interview schedule comprised a combination of free-flow narrative and a semi-structured interview. Participants were first asked to tell their story in their own words. The purpose of this was to enable participants to relax and facilitate memory recollection and uncover experiences and situations in the WTC evacuation that might not previously have been considered by the researchers. The free-flow narrative was followed by a semi-structured interview, during which the interviewer confirmed and expanded upon details previously provided in the free flow and sought to ascertain more specific information regarding the participant's entire experience relevant to the



(a) (b)

Figure 1. Two still images taken from animated demonstrations of Fruin Level of Service C (blue) and F (orange): (a) Fruin Level of Service C (blue): 1 person/m^2 and (b) Fruin Level of Service F (orange): 3 persons/m^2.

specific areas of research interest. For example, participants were asked a series of group-related questions designed to illicit information concerning group formation, group dissolution, type of assistance rendered by the group, etc. Participants were also asked a series of questions relating to for example, perception of risk, the nature of activities they were involved with just prior to and just after they perceived the need to evacuate, merging behaviours on the stairs, etc. Throughout the interview, interviewers attempted to extract from the participant as much contextual information relating to time and location of the described experiences. For example, it was considered important to determine an estimate for the actual time (absolute) that something occurred, and the time taken for certain events to occur, e.g. waiting in line, firefighters to pass. Interviewers also attempted to establish where the participant was when this occurred (floor level, location on floor). Where absolute times could not be determined they tried to determine the times that things were occurring relative to global time markers, e.g. time WTC2 hit, time WTC2 collapsed. This information was crucial to address specific engineering research questions related to, e.g. response times, travel speeds, etc.

To quantify participants' experiences of crowd densities during the stair descent, computer generated animations of people descending stairs based on the classic Fruin densities (also often referred to as Level of Service or LoS) [14] were periodically administered. These animated images were introduced whenever the participant entered or exited a stairwell, and whenever they mentioned crowding on the stairs. This information, together with information about time periods where important events occurred on stairs, assists in identifying travel speeds on stairs and associated crowd densities. The animated sequences were generated using the buildingEXODUS [9] software and animated using the vrEXODUS [9] software as shown in Figure 1.

During the interview, participants were also asked to complete risk perception and organizational structure questionnaires. The risk perception questionnaire comprised a general question on how at risk they felt at the time (rated on a seven-point scale, from 1 'no risk' to 7 'very high risk') and why, followed by a series of statements related to different risk attributes, identified from risk perception studies, e.g. information available, control, dread, etc. to which they had to rate their level of agreement. Participants were asked to complete the risk perception questionnaire up to four different times during their evacuation, i.e. at WTC1 impact, when the participant was deciding to evacuate, when the participant knew that WTC2 had been hit (if applicable) and when the participant knew WTC2 had collapsed (if applicable). The semi-structured interview was piloted in New York over a period of six weeks. From the pilot study it became apparent that there were at least seven distinct phases that evacuees experienced during 9/11, namely: pre-recognition, recognition, response, horizontal evacuation, vertical evacuation, evacuation interruption (where participants chose to interrupt their evacuation, e.g. after the public announcements in WTC2) and exiting the WTC complex. These phases constitute a new model of evacuation behaviours and as such informed the development of the database.

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CODING PROCESS AND THE DEVELOPMENT OF THE HEED DATABASE

The HEED database is developed in Microsoft (MS) Access and is specifically designed to store and retrieve coded HEED WTC evacuation data from interview transcripts. The information stored in the HEED database provides a means to address key research questions relating to human factors issues associated with evacuation from high-rise buildings (see [4, 7] for key research questions). The HEED database was developed from a content analysis of a small subset of participants' interview accounts. The content analysis indicated that participants' evacuations comprised a variety of complex and detailed experiences ranging from observations and interpretations of events to subsequent feelings and actions. From the content analysis, a three-level Experience structure was devised in order to systematically categorise participants' rich evacuation experiences into mutually exclusive categories. Data within HEED are stored using the logical arrangement of the three-level Experience hierarchy. In addition to coded Experience information, the HEED database also includes the full transcripts for each interviewed participant and the pre-interview questionnaire responses. The HEED database captures all of the participants' evacuation experiences such as stimuli (e.g. observational cues), cognitions (e.g. incident interpretations) and individual and group behaviours (e.g. actions and reactions) within the three-level Experience hierarchy. Supporting information such as the time of an experience and participant's location are captured by associated contextual information. The highest level of the hierarchy is the Experience Category or Level 1 experience. There are six core experience categories, namely: Action, Sensory, State, Cognition, Dialogue and Risk Perception. Below the Experience Category is the Experience Type or Level 2 experiences which identify the nature of the experience. The final element in the hierarchy is the actual Experience extracted from the text, also referred to as the Level 3 experience. The hierarchical experience structure can be thought of simply as short cut menus leading to the appropriate Level 3 experience [4]. Before the experience can be coded into the database it must first be identified. This is achieved by editing the interview transcripts into Behavioural Patterns (BP). BPs are chunks of transcript text which contain experience and corresponding contextual data. Once a BP is identified the relevant experience codes and contextual information relating to the experience are determined and coded into the database, along with the actual BP and its location within the transcript. A BP can have several mutually exclusive experience categories attached. As part of the data entry, the entire edited transcript of the interview is linked to the database, as is factual information obtained from the pre-interview questionnaire. Names of people and companies are removed from all entries, being replaced with coded IDs, ensuring that the identity of the participant remains confidential.

In addition to coding the Level 3 Experience, 'contextual information' is required to clarify the details of the experience. For example, the contextual information could be the time at which the experience occurred or an estimation of the crowd density when the experience occurred. As noted earlier, crowd density estimations are provided by the participant during the semi-structured component of the interview using a specially devised Fruin-based tool. The time at which an experience occurred is represented within HEED in several ways. It can be actual or estimated times provided explicitly by the participant during the interview or a time interval estimated by the research team based on the evidence provided within the transcript. The time interval data coded in the HEED database consists of 14 specific time intervals and four specific key times. The time intervals are defined around the four key times, namely the impact into WTC1 at 8:47am (T1), the impact into WTC2 at 9:03am (T6), the collapse of WTC2 at 9:59am (T12) and the collapse of WTC1 at 10:28am (T18) (note that the naming convention for the time intervals used in this paper is slightly different to that used in earlier papers). As an example of this process, consider the time span between T1 and T6. This was divided into four sub-intervals as follows:

- T3 being the sub-interval 'Between T1 and T6', i.e. 08:47 < event time < 09:03,
- T2 being the sub-interval 'Closer to T1 than T6', i.e. 08:47 < event time < 08:55,
- T4 being the sub-interval 'Closer T6 than T1', i.e. 08:55 < event time < 09:03 and
- T5 being the sub-interval 'Shortly before T6', i.e. 09:02 < event time < 09:03.

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The first four time intervals (times in minutes measured from WTC1 impact) are, (0–8), (0–16), (8–16) and (15–16). The process of estimating the time when an event occurred involved the analyst reading the interview transcript and from the evidence provided determining which time sub-interval best captured the event time.

DATA ANALYSIS

A vast amount of data was collected from the HEED interviews. In total 271 persons who evacuated the WTC on 9/11 were interviewed, 129 from the North Tower (WTC1) and 125 from the South Tower (WTC2), generating almost 6000 pages of interview transcript. Analysis of these data will continue long after the formal end of project HEED. Here, we present a portion of the data analysis conducted thus far by FSEG. Please note that the analysis presented here is the most recent analysis and contains more data than presented in an earlier publication [7]. Of the 271 people interviewed, 63.6% of the WTC1 population and 59.2% of the WTC2 population were males. The mean ages of the populations are 46 and 42.5 years of age for WTC1 and WTC2, respectively. The oldest person interviewed was 68 years of age (in both towers), whereas the youngest person interviewed was 24 and 22 years of age in WTC1 and WTC2, respectively. Of the population interviewed, 29 and 18% of the WTC1 and WTC2 population respectively had worked in the WTC towers for less than 12 months, whereas 22 and 21% of the WTC1 and WTC2 populations respectively had experienced the 1993 bombing and evacuation. The majority of people interviewed were located in the upper third of the WTC1 and WTC2, i.e. 42% of the WTC1 sample and 57% of the WTC2 sample were located on floors above the 60th floor. The Body Mass Index (BMI) of the sample was also determined. The BMI is defined as the individual's body weight divided by the square of their height and is used to assess how much an individual's body weight departs from what is normal or desirable for a person of given height. For Western European and North American adults a BMI of: less than 17.5 may indicate anorexia; between 17.5 and 18.5 suggests the person is underweight; between 18.5 and 25 indicates optimal weight; between 25 and 30 suggests the person is overweight; between 30 and 40 the person is obese and over 40, the person is morbidly obese. For the WTC1 sample, 63% of the population was in the overweight/obese categories with 5% of the population in the morbidly obese category. For WTC2 population, 74% of the population was overweight/obese, whereas 4% of the population was in the morbidly obese category. A total of 68% of the sample population were in the overweight/obese categories. Finally, the level of fitness of the participants was gauged from the response to the questionnaire and was classed as being physically active or not. This in turn was based on the National Health Service recommendations of engaging in 30 min of moderate intensity activity for five or more days per week. Some 64% of the WTC1 participants were not considered physically active based on this measure. In addition, 15% of the WTC1 sample were smokers and 24% had medical conditions that might affect their general fitness and/or mobility, e.g. respiratory problems, hypertension or arthritis.

Frequency of stops

The number of times evacuees stop during their descent is an important parameter as it will impact the average travel speed of the individual. The reason why evacuees stopped is also important as it addresses issues associated with environmental conditions on the stairs and the possible contribution that the population demographic may have on the occupant performance on the stairs. Several recent WTC studies [1, 3] have reported lower than expected average stair travel speeds. Unfortunately, due to a lack of data in both these studies, it was not possible to determine why the travel speeds were so low. There has been considerable discussion in the literature that the growing obesity epidemic [15] may be adversely affecting the ability of building occupants to travel large distances on stairs during building evacuations and may be the cause of the lower than expected average travel speeds found in these studies.

For these reasons stoppage data was extracted from the transcripts of 124 WTC1 participants (those evacuating from above floor 2). The data suggested that 85% (106) of the participants

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Table I. Number of people reporting stops in WTC1.

Floor region	No stops	Stopped at least once	Total
High: 61–90	7	47	54
	13%	87%	100%
Mid: 31–60	5	41	46
	11%	89%	100%
Low: 1–30	6	18	24
	25%	75%	100%
Total	18	106	124
	15%	85%	100%

stopped at least once, and of these, 22% stopped once, 9% stopped twice, 2% reported stopping at least 20 times and 42% made an unspecified number of multiple stops during their descent. A total of 388 discrete stop incidents were reported by the participants. Congestion was the most frequent cause of stoppages, being reported by 58% of the population and causing 43% of the stoppages. The next most frequent cause of stoppages were by descending groups of people, often injured (17% of stoppages), or people ascending, typically firefighters (16% of stoppages). In these situations the participants would interrupt their descent to allow the injured/firefighters to pass. These types of incidents were reported by 33 and 39% of the population, respectively. The third most common cause of stopping was fatigue—the need for someone, usually the participant's companion(s), to take rest—with 8% of the reported stoppages due to this reason. Rest stops were reported by 17% of the population. The fourth most common cause of stoppages was due to environmental conditions. A total of 7% of the reported stoppages were caused by environmental conditions such as debris, smoke, heat, water on the stairs, etc. This type of stoppage was reported by 19% of the population. The stoppage frequency is summarized in Table I. We note that at least 75% of the sample from each of the three floor regions reported stopping at least once however, participants in the High and Mid levels were more likely to stop during descent than those in the Low levels. This information relates to stoppages of all kinds and so does not distinguish between people requiring rest stops and those that stopped due to congestion or other issues. It is clear from these data that there were frequent interruptions to the steady descent of evacuees which would have contributed to the smaller than expected travel speeds. In addition, it appears that the higher in the building the evacuee starts the evacuation, the greater the likelihood of stopping due to the greater chance of being subjected to the various stoppage reasons. In addition, over 90% of all reported stoppages were caused by reasons other than fatigue. Most participants did not feel the need to take rest stops. This applied even to people located in the upper part of the building and in the Overweight/Obese BMI category.

For example, consider the following statement from a participant who started his evacuation from the 73rd floor with a BMI of 27 (Overweight):

WTC1/073/0001, Page 22 L24-37
I: Did you ever get tired yourself and have to stop and rest?
P: Physically, no… I mean I encountered several people though that were experiencing difficulty getting out……… so there were people depending on your physical age and condition and whatever that struggled… I don't mean to make light of…
I: No, no, it's okay.
P: That it was 'a walk in the park'… but me personally, I never felt physically challenged…..

While this person started his evacuation from the upper third of the tower and was classed as 'Overweight', he did not feel the need to take a rest stop. However, this person reported stopping two times due to congestion.

While few participants (only five) reported stopping specifically because they personally felt fatigued during their evacuation, there were cases where participants said they stopped because

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Table II. Number of people requiring rest stops in WTC1.

Floor region	No stops	At least 1 rest stop	1 Rest stop	2 Rest stops	3 Rest stops	4 Rest stops	Unspecified multiple stops	Total
High	7	**13**	8	2	0	1	2	20
61–90	**35%**	**65%**	40%	10%	0%	5%	10%	100%
Mid	5	**2**	0	0	1	0	1	7
31–60	**71%**	**29%**	0%	0%	14%	0%	14%	100%
Low	6	**3**	2	0	0	0	1	9
1–30	**67%**	**33%**	22%	0%	0%	0%	11%	100%
Total	18	**18**	10	2	1	1	4	36
	50%	**50%**	28%	5%	3%	3%	11%	100%

their companion(s) (18 reported, not interviewed) were fatigued. In the following analysis we compared data on people (participants and companions) who needed to stop and rest with data on the 18 participants who reported making no stops at all during their evacuation. Note that two companions were excluded as they were disabled, leaving a total sample of 39 individuals for rest stop analysis (36 individuals shown in Table II plus 3 individuals for which floor information was not available). Note also that as the companions were not interviewed, certain demographics (e.g. BMI score, floor they began evacuating from) was not directly available. However, participants' descriptions of their companions allowed for estimates (e.g. whether overweight/obese) to be made in many cases.

Approximately two thirds of the sample in the High region required rest stops while only a third or less of the sample in the Mid and Low regions required rest stops. Furthermore, approximately a quarter of the sample in the High and Mid region required multiple rest stops (see Table II). As regards the people's physical characteristics, it is interesting to note that 85% of people who stopped and rested were female, whereas only 50% of people not stopping were female, and that at least 62% of people resting had medical conditions while only 11% of the no stoppers did. The percentage of people stopping to rest who were overweight/obese (69%) was similar to that of people who did not stop during their evacuation (72%). This information suggests that BMI does not appear to be an indicator of whether a person was fatigued to the point that they required a rest stop. It should be noted that 65% of the WTC1 population surveyed were in the overweight/obese categories. The level of fitness of people who stopped due to fatigue versus those who did not stop was also considered. While the sample size was small and fitness information was missing in some cases, the individuals who stopped due to fatigue were, for the most part, no less fit than the individuals who did not stop during the descent—60% of rest stoppers were not physically active compared with 67% of no stoppers. Thus, BMI and level of fitness do not appear to be indicators of whether or not a rest stop is required.

However, when participants stopped due to congestion, they were also resting. This is demonstrated by another participant who started on the 69th floor and had a BMI of 37 (obese):

WTC1/069/0001, Page 16 L21-27
I: Did you ever stop to have a break to have a rest?
P: Never no.
I: Nothing like that.
P: Only when I was forced, when it wasn't moving.
I: When it wasn't moving, yes.
P: Then I would sit on the step and I was watching and watching and someone would say okay we are moving now …

By default, participants forced to stop due to congestion or other external reasons were also resting and recovering. This may mask the effect of BMI in causing the participants to take a rest stop. To put the need to rest into perspective it is worth noting the total travel distances associated with descending from various levels within the WTC buildings. Using Stair C as the egress route and assuming that the central route down the stairs is taken, the total travel distance from 110th

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floor to the 2nd floor is estimated to be 1439 m; from the 90th floor, 1192 m; from the 60th floor 755 m and from the 30th floor, 345 m.

Stair travel speeds

Several WTC studies [1, 3] have reported lower than expected average stair travel speeds. The UK BDAG study [3] first reported lower than expected travel speeds derived from their sample of survivor accounts published in the public domain. Their relatively small sample of useable data suggested a mean speed of 0.24 m/s. The later NIST report [1], based on a larger sample of first-hand survivor accounts suggested an even lower mean travel speed of 0.2 m/s. To put these values into perspective it is worth noting the data reported by Fruin which is often used in engineering analysis [14]. Fruin measured free flow stair travel speeds of 700 males and females of various ages, both descending and ascending stairs. For males aged 30–50 descending stairs, his data produce a mean speed of 0.88 m/s (4.2 floors/min) while for males aged over 50 his data suggest a mean speed of 0.69 m/s (3.3 floors/min) [14]. In recent correspondence between Galea, Pauls and Fruin, it was noted that the free flow stair data measured by Fruin was over only one or two flights of stairs and so does not include the potential impact of fatigue on stair travel speeds [16]. As a result, Galea suggests that this data should be used with care in high-rise building applications. Other data often quoted concerning stair travel speeds are derived from observations of high-rise building evacuation drills which suggest a mean speed of 0.52 m/s (2.5 floors/min) in optimal flow conditions and 0.22 m/s (1.1 floors/min) in crush conditions [17]. As a reference, it is worth noting that for Stair C of the WTC a speed of 1.0 floors/min is equivalent to 0.21 m/s while 3 floors/min is equivalent to 0.62 m/s. Estimating the stair travel speed from participant transcripts is a difficult and time-consuming process. Thus far we have restricted our analysis only to people who completed their journey from start to finish on a single stair. Analysis is further restricted to individuals for which we have a reasonable estimate of when they entered the stairs and when they left the stair. An individual's journey between the beginning and end points is reconstructed from information provided in the interview transcript, noting events such as:

- Environmental conditions encountered—where and when?
- Encountering firefighters—where, when, how long?
- Encountering injured being carried down—where, when, how long?
- Encountering congestion—where, when, how long, Fruin density?

In reconstructing segments of the journey it is often necessary to make some assumptions concerning aspects of that part of the journey e.g. duration of stoppage if not provided. In addition, sometimes it is necessary to estimate the speed in terms of floors/min based on the provided Fruin density and description of movement, e.g. if Fruin F estimated and participant describes very slow movement, we assume approximate speed of 1 floor/min—unless other evidence is provided to suggest a faster speed. Where it is not possible to make reasonable estimates of journey segments, a simple average speed is determined for the journey from beginning to end. The following extract from an account demonstrates an estimation made by the participant of the crowd density (Fruin density F = orange) at floor 55, how he travelled very fast down the stairs from floor 60 to 55 and then came to a stop when encountering the Fruin F.

WTC1/060/0001 P11 L24-40
I: Okay, so that's Orange. And so when it got congested, did you say this was because other people were coming into the stairs?
P: Yes, other people were coming in as well as already in the stairwell from whatever floor they had come from.
………
I: And how did that affect the travel speed?
P: It slowed down dramatically.
I: So, were you having to stop at any point?

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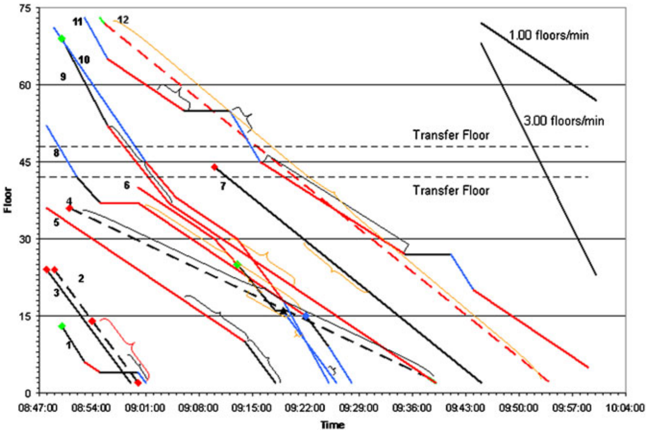

Figure 2. Floor vs time diagram for 12 evacuees using Stair C (refer to the on-line version of the paper to view figures in colour).

P: We stopped at 55, right there, because there was obviously a lot more people. I mean we were running down for the first five stairs, "Boom, boom, boom, boom, boom", two stairs at a time sometimes. When we got to 55, we couldn't do that because we would plough into people ....

Using this type of information it is possible to construct a 'Floor–Time' diagram for the participant. The diagram provides a very useful way of visualizing the progressive evacuation of a high-rise building. When used forensically in reconstructing an evacuation based on first-hand survivor accounts, it also provides a means of corroborating the accounts of the evacuees, checking the consistency of assumptions in reconstructing the path and filling in information gaps in the accounts of some evacuees. Depicted in Figure 2 is a Floor–Time diagram for 12 evacuees who used Stair C that meet the criteria described above. The numbers on the curves indicate the participant ID, e.g. 2 refers to participant WTC1/021/0001 (BMI 18.6) who started his evacuation on the 21st floor. The slope of the line or line segment represents the speed of the participant in floors/min. For participants 2 and 12 the average travel speeds are 2.0 floors/min and 1.2 floors/min, respectively. These speeds can be converted to an approximate speed in m/s using the approximate 12.3 m travel distance estimate or a more accurate conversion can be derived using the actual travel distance for the floors covered, including transfer corridors, the latter is used here where possible. There are several innovations to the standard Floor–Time diagram that have been introduced in this project to convey additional information relating to the descent of the individuals. Each line segment is coloured according to the Fruin density that was reported by the individual. Black indicates that no Fruin density was reported, blue indicates Fruin densities of A ($<0.5\,p/m^2$) or B (0.5–$0.7\,p/m^2$), green indicates Fruin densities of C (0.7–$1.1\,p/m^2$) or D (1.1–$1.4\,p/m^2$) and red indicates Fruin densities of E (1.4–$2.5\,p/m^2$) or F ($>2.5\,p/m^2$). Coloured squares indicate a spot Fruin density only at the specified location. A dashed line indicates that there were complications along the egress route that makes the path unrepresentative of the travel speeds that one would normally expect, even for the level of congestion encountered. For example, participant 2 suffered from a serious pre-incident medical condition which made his travel speed unrepresentative, whereas participant 4 reported stopping 10–20 times during the descent and participant 12 was reluctant to overtake the people in front of him who were carrying a disabled person down the stairs.

Various types of brackets are also shown along some of the journey segments. These are used to represent the presence of factors that may impact the travel speed. A curved bracket indicates that the factor occurred somewhere in the region indicated but a precise location was not provided while a square bracket indicates that the factor persisted over the entire region indicated. The colour of the bracket also carries some significance. Gold indicates the presence of firefighters ascending the stair which interfered with the participants' downward progress, red indicates a Fruin density

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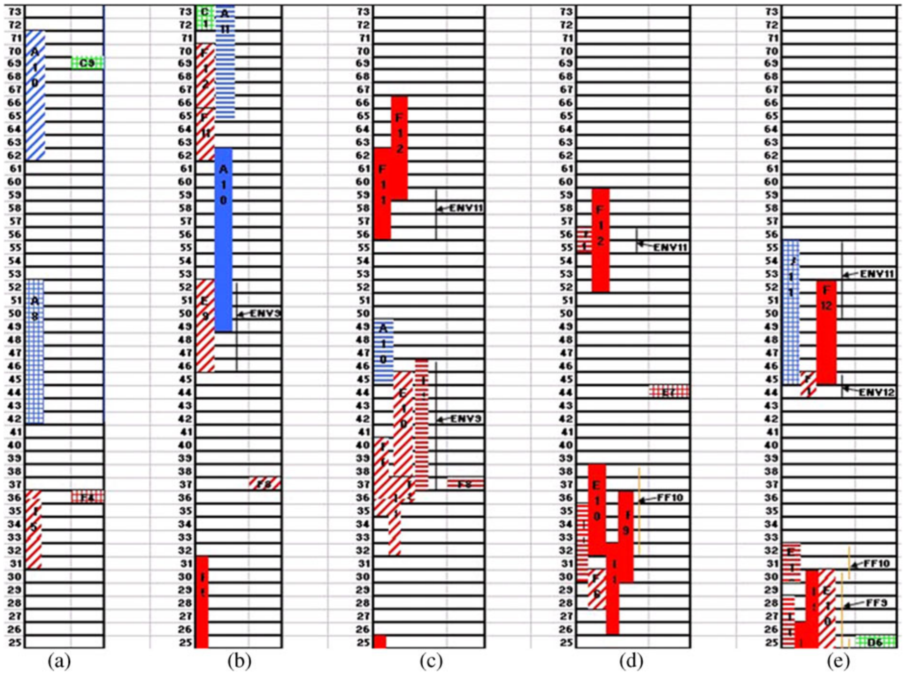

Figure 3. Fruin map of North Tower Stair C showing floors 25–73 in 6-minute time slices: (a) 8:47–8:53; (b) 8:53–8:59; (c) 8:59–9:05; (d) 9:05–9:11; and (e) 9:11–9:17 (refer to the on-line version of the paper to view figures in colour).

of E or F and black indicates the presence of environmental factors such as smoke, heat, dust, water or debris which impacted the progress of the participant. For complicated paths such as 1 or 11 a travel speed can be determined for each segment of the journey and an overall average speed can be determined by simply taking the beginning and end points. For participant 1 the average travel speed for the journey from floor 13 to floor 2 is 1.0 floors/min (0.21 m/s) while for participant 11 the average travel speed from floor 73 is 1.03 floors/min (0.22 m/s). Note that both these participants have periods during their journey where they have passed through high crowd density regions (Fruins E and F) and participant 11 has stopped his journey on two occasions. As can be seen from Figure 2, when the participant passes through high crowd density regions their travel speed, measured by the slope of the line, is less than when they travel through lower crowd density regions. Using the Floor–Time diagram we thus note that at times participant travel speeds can be considerably higher than suggested by taking the simple average travel speed. Furthermore, we can also measure the impact that the stoppages and high crowd densities can have on the average travel speed. This may begin to explain why the early BDAG [3] and NIST [1] studies found lower than expected travel speeds.

Using the information provided by the interview transcripts it is possible to construct a Fruin Map of the WTC buildings. The Fruin map provides an indication of the crowd densities on the stairs as reported by the survivors. In addition, information relating to the environmental conditions on the stairs and the location and time at which firefighters were encountered can also be recorded. The Fruin map displays each floor in the tower and indicates the conditions on the stairs in small time slices. Presented in Figure 3 is an example of a portion of the Fruin Map for Stair C showing floors 25–73 in 6-minute time slices. Each entry in the Fruin Map is derived from a survivor statement. The coloured bars represent the Fruin density as described in Figure 2. In addition, the coloured bars are numbered so that the particular statement can be found (numbering same as used in Figure 2) and the coloured bar also carries the actual Fruin density. The coloured entries that cover only a single floor represent the Fruin density estimates provided by the participants on entry into the staircase. As the time slices used in the Fruin map are of finite duration, the crowd density observation provided by the evacuee may not cover the entire duration of the imposed time

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slice. To reflect this, a fill pattern has been introduced that describes the portion of the time slice that the observation is valid for. A solid fill suggests that the observation is valid for the entire duration of the time slice. A hash fill indicates that the observation starts after, and ends before the time slice. Horizontal bars indicate that the observation ends before the specified time period while diagonal bars indicate that the observation starts after the beginning of the specified time period. Using this system many of the apparent conflicts in crowd density may be explained. In addition, vertical gold lines indicate the presence of firefighters while vertical black lines indicate that adverse environmental conditions were encountered.

The Fruin map can be used in conjunction with the Floor–Time diagram to fill in gaps in the Fruin density information provided by some of the participants. This enables a better understanding of the environment through which the participants travelled. Putting all this information together provides a possible explanation for the apparently low average travel speeds observed. First, the travel speeds of four individuals (1,6,8,11) can be adjusted upwards by taking into account the identified stops. Second, two individuals (4,12) had low travel speeds due to complicating factors, i.e. one was travelling behind a group carrying a disabled individual and did not wish to overtake (12), while the other person had pre-existing medical conditions which effectively meant that he had a movement-related disability (4). Using this sample of 10 people produces (see Table III) an average stair speed of 0.33 m/s for occupants on Stair C. A similar analysis was completed for Stairs A and B which produced average stair speeds of 0.25 m/s derived from 13 occupants on Stair B and 0.31 m/s derived from seven occupants on Stair C. Using the results from all 30 occupants produces an average stair travel speed of 0.29 m/s. While this speed is 45% larger than the average reported in the NIST study [1] it is still relatively low. Further analysis of the travel speed data reveals that those individuals with average travel speeds lower than the group mean speed experienced high crowd densities for at least 60% of their journey (see Table III for Stair C), with the lowest calculated average travel speed of 0.17 m/s (ID, 49/0001, Stair B) corresponding to an individual who spent 94% of his journey in high crowd densities, while those with average travel speeds higher than the group mean travel speed spend only short parts of their journey in high crowd densities. We can also consider average travel speed as a function of BMI. The average speed for the various BMI categories are: optimal, 0.29 m/s (10 individuals); overweight, 0.28 m/s (14 individuals); obese, 0.29 m/s (3 individuals) and morbid, 0.28 m/s (2 individuals). For users of Stair C for which we have travel speed data (10), 40% (4) of the sample were considered to be fit. Taken across all three stairs, for the users for which we have travel speed data (30), 40% (12) of the sample were considered fit. We find no correlation between travel speed and fitness. These results suggest that BMI and fitness is not a predictor of stair travel speed and that the low average stair speed observed for participants may simply be due to the relatively high crowd densities encountered during the descent. However, the impact of crowd density may mask the effect of BMI and fitness.

Table III. Travel speed and percentage of journey subjected to various crowd densities for Stair C.

ID WTC1	Graph ID	BMI	Physically active	Unknown Fruins (%)	Low Fruins (A,B) (%)	High Fruins (E,F) (%)	Original average speed (m/s)	Average adjusted speed (m/s)
13/0002	1	28	No	50	25	25	0.21	0.38
21/0001	2	19	Yes	87	—	13	0.41	0.41
24/0001	3	26	Yes	96	—	4	0.41	0.41
36/0002	4	28	Yes	91	—	3	0.15	0.15
36/0003	5	48	No	23	—	77	0.23	0.23
40/0001	6	24	No	0	38	64	0.30	0.31
44/0002	7	37	No	98	—	2	0.25	0.25
52/0004	8	25	No	10	49	45	0.27	0.31
69/0001	9	37	No	0	24	75	0.29	0.29
71/0004	10	26	No	0	63	40	0.41	0.41
73/0001	11	27	Yes	0	41	68	0.22	0.27
73/0003	12	33	Yes	96	—	1	0.26	0.26

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Table IV. Response time distribution for WTC1.

Region	Rapid <1 min	Moderate 1–8 min	Long >8 min	Total
High: 61–90	8% (4)	86% (43)	6% (3)	50 (42%)
Mid: 31–60	16% (7)	71% (32)	13% (6)	45 (38%)
Low: 1–30	17% (4)	75% (18)	8% (2)	24 (20%)
Total	13% (15)	78% (93)	9% (11)	119

Response times

The occupant response times coded into the HEED database proved too coarse to allow meaningful analysis of response times for WTC1. As a result, the FSEG team defined four additional time intervals (18 time intervals and 4 key times) and recoded the response time data as described above. As a result, the response times for WTC1 were coded into 1 of 10 time bands (measured in minutes from WTC1 impact), namely: **(0–1)**, **(1–4)**, (1–8), (1–16), (8–16), **(12–16)**, **(16–21)**, (16–26), (16–72), (44–72). A total of 119 response times were derived from the transcripts. Owing to small samples within the above time bands, data were further collapsed into three broad response time groups, i.e. Rapid (<1 min), Moderate (>1 and <8 min) and Long (>8 min) and the vertical spatial distribution of the building was split into three broad categories Low, Mid and High as shown in Table IV.

From Table IV we note that within each floor group, over 70% have Moderate response times and overall almost 80% of the sample has Moderate response times. In addition, the High region has the largest Moderate response time group and the smallest groups with Rapid and Long response times. The relative low numbers of rapid responders high in the building is thought to be due to the relative proximity to the incident, with the sample in this part of the building experiencing the most severe physical effects resulting from the impact and as a result not being able to react as quickly as people elsewhere in the building. Similarly, this region has the lowest number of Long responders. Again, having experienced the most severe physical affects of the impact, this group was less likely to delay their evacuation.

In addition to the time taken to react, the nature of the tasks undertaken during the response phase was examined. Two types of tasks were considered, *Information Seeking* and *Action* Tasks. The *Information Seeking* tasks involve participants attempting to gather information prior to commencing their evacuation. Examples include: sought environmental information; sought information from colleagues, authority figures, etc.; waited for further info, etc. *Action* tasks involve performing physical actions prior to the commencing horizontal evacuation. Examples include: collect items; searched office/floor; instructed others to evacuate; shut down computer; secured items (locked safe); changed footwear; etc. A total of 469 tasks were completed by 119 participants, 175 *Information Seeking Tasks* and 294 *Action Tasks*. It should be noted that a number of participants completed the same type of task more than once. A positive significant relationship was found between total number of tasks completed and response time $\tau = 0.51$, p (one-tailed) <0.01, i.e. the more tasks completed the longer the response time. On average a person completes four tasks (1.5 *Information* and 2.5 *Action Tasks*) prior to starting to evacuate. Half the samples (50.4%) undertake three or less tasks in total prior to entering the stairs. In addition, three fifths (59.7%) of the samples undertake up to two *Action Tasks* while three fifths (60.5%) of the population undertakes up to one (i.e. none or one) *Information Seeking Task*. The two most common *Information Seeking Tasks* were, ‘Sought environmental information’, reported 64 times (37% of all Information Seeking Tasks) and, ‘Sought information from friends/colleagues’, reported 44 times (25% of all Information Seeking Tasks). The two most common *Action Tasks* were, ‘Collect Items’, reported 143 times (49% of all Action Tasks) and ‘Instructed Others to evacuate’, reported 52 times (18% of all Action Tasks).

Clearly, participants undertake a number of tasks prior to starting their evacuation. As it was not possible to determine a unique response time for each of the participants the upper end of the response time band associated with each participant was used to represent the maximum likely

Table V. Average maximum response time associated with various task types.

Type of tasks ‘0 Action and’	Average max response time (min)	Sample size	Type of tasks ‘0 Info and’	Average max response time (min)	Sample size
0 Info	1.8	11	0 Action	1.8	11
1 Info	4.0	5	1 Action	2.9	11
2 Info	4.0	3	2 Action	4.0	6
3 Info	6.0	2	3 Action	4.0	2

response time for an individual undertaking a particular set of tasks. Using this information it is possible to estimate the response times associated with undertaking those tasks (see Table V). We note that starting the evacuation without undertaking any tasks results in the shortest average maximum response time, requiring only 1.8 min. This is an indication of the average minimum time required by an individual to start their evacuation in this type of incident. It represents the time required to overcome the initial disorientation created by the incident, decide to evacuate and begin to purposely move towards the exit stairs. However, in general an individual may perform ‘n’ *Information Seeking Tasks* and ‘m’ *Action Tasks* prior to starting their evacuation. As data presented in Table V consider response times associated with individuals undertaking only Information Seeking Tasks or only Action Tasks it is thus possible to determine the average time to perform a single Information Seeking Task and a single Action Task. This is determined by subtracting 1.8 min from the total response time and dividing it by the number of tasks completed.

Applying this approach to the data in Table V (and taking an average for 1, 2 and 3 tasks completed) produces an average maximum time to undertake a single *Information Seeking Task* and *Action Task* of 1.56 min and 0.97 min, respectively. Thus the time required to undertake an *Information Seeking Task* is some 1.6× longer than the average time to undertake an *Action Task*. Of interest is the result that *Information Seeking Tasks* appear to take longer on average than *Action Tasks*. It is suggested that the frequency and number of *Information Seeking Tasks* could be reduced or removed completely if appropriate information could be provided to evacuees via hardened buildings communication systems. Furthermore, it is suggested that the frequency and number of *Action Tasks* could be reduced or removed completely if appropriate training and clear instructions are provided to building occupants.

Finally, the perceived risk when the participant decided to evacuate (R2) was compared with their maximum response time. This could be done for 91 participants for which we have a (R2) risk and a maximum response time. Participants with Low Perceived Risk (rating 1,2) have the highest average maximum response time of 6.7 min (13 individuals) while those with High Perceived Risk (rating 6,7) have the shortest average maximum response time of 5.3 min (30 individuals). Thus those who perceive a high risk respond 1.26× faster than those who perceive a low risk.

Evacuation modelling

As part of project HEED a detailed analysis of the evacuation of WTC1 was undertaken using computer simulation [9, 10]. The modelling was performed using the buildingEXODUS evacuation simulation software [18, 19]. Here we summarize the main findings of this work, full details of the simulations can be found in [9].

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 [20–22]. 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. However, given the complexity of the building, the geometry is kept as simple as possible while capturing all of the significant features.

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Within the model the population was distributed only on the rented floors. Thus the floors known to have no tenants such as machine floors, etc. were left unoccupied. This meant that there were no people on floor 1 (lobby); floors 2–6 (not rented); floors 7–8, 41–42, 75–76, 108–109 (mechanical floors), floors 44 and 78 (sky lobbies) and 110 (television studio). It should be noted that the Windows in the World restaurant was located on floors 106–107. In total two different-sized populations consisting of 9650 and 25 500 people were considered.

The 9650 population case is intended to represent the maximum number of people thought to have been in WTC1 at the time of the attack. This represents the population upper limit as estimated by NIST. From the NIST estimates it is thought that 1462 people in WTC1 died, this included essentially everyone above the 91st floor (i.e. floors 92–110) and a few people on the lower levels [1], resulting in 8188 survivors able to evacuate from WTC1. As complete and conclusive information concerning how these people were distributed throughout the building is not known, we assume that the population was distributed evenly amongst the remaining 77 floors producing an average number of 107 people per occupied floor and a total of 8239 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 4384 are assumed to be either impact victims or trapped above the impact floors.

The firefighters were included in some of the scenarios investigated. Accurate information regarding the number of firefighters who entered the stairs of WTC1 at precise times and precise entry points was not available. For the scenario involving firefighters, 300 firefighters were injected into Staircase B. From the NIST report [23] the fire department set up their command post in the lobby of WTC1 at around 08:50. By 09:00 there were five fire department units at the scene and by 09:15 some 30 units [23] had arrived on the scene. Various media accounts suggest that firefighters began climbing the stairs at 08:55. Within the analyzed scenario, the firefighters start their ascent of the stairs at 09:00, 14 min into the simulation.

Within the simulation, the firefighters were generated in teams of 10, each member of the team entering the staircase in a 30 s burst with a 1 min break before the next team was generated. Thus the first firefighter was generated after 14 min and the last after 58 min. Using the *itinerary* capability available within the software, each firefighter was assigned the task of ascending the stairs up to the 50th floor. The model settings describing the physical attributes for all the firefighters were identical. They assumed the default software settings for 30-year-old males, with several important changes. The firefighter travel speed up the stairs was reduced from the default software value. This was intended to represent the fact that the firefighters would be carrying a considerable amount of equipment and that fatigue would set in during the ascent. It was reported that the firefighters could have carried 23 kg (50 lb) of standard equipment, including breathing apparatus and some of them would also carry an additional 23 kg (50 lb) of other emergency equipment [23]. It was also reported that in attempting to ascend to 30 floors or more, firefighters required an average of 1.4 min/floor if not carrying equipment and about 2.0 min/floor if carrying equipment [23]. This speed represents an average which includes rest periods. In addition, these average travel speeds also take into consideration degradations in travel speeds resulting from congestion-related interactions with the evacuating building population. Within the simulation software, it is essential to specify the maximum unhindered (by congestion) travel speeds as the software factors in the effects of congestion as part of the simulation. The travel speeds cited in the NIST report are therefore likely to be too slow for use within the simulation.

A UK study into firefighter physiological performance [24] involving a series of controlled experiments using firefighters under a variety of different work loads including performance in high-rise buildings. The high-rise trials involved firefighters climbing 28 floors with varying degrees of equipment. Trials involved firefighters only carrying their Personal Protective Equipment (PPE); PPE and Extended Duration Breathing Apparatus (EDBA), weighing on average 32 kg; and PPE,

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Table VI. Summary of results for Scenario 1 (average across 50 repeat simulations).

Scenario 8239 survivors	Average total evacuation time
(1a) Survey response times	1 h 24 m 33 s
(1b) Engineering response times	0 h 55 m 31 s
(1c) Instant response time	0 h 53 m 04 s

EDBA with different hose combinations adding 11.5 kg, 13.5 kg or 15 kg depending on the type of hose carried. During the trials the firefighters took as many as eight breaks while ascending the stairs. The average time (including rest periods) for the firefighters to climb 28 floors with only PPE was approximately 7 min while with PPE, EDBA and hose it was approximately 14 min. This suggests that stair speeds vary between 0.25 min/floor and 0.5 min/floor depending on the load carried and without interacting with building occupants travelling down the stairs.

The number of floors travelled by firefighters in the WTC is thought to be greater than that experienced in the UK trials. As the number of floors increases, the number of required rest periods and required recovery time will increase while the recovery speed will decrease. While the simulation software does not currently include a fatigue model, it would have been possible to insert into the itineraries of the firefighters rest periods of fixed duration after ascending a certain number of floors. However, as sufficient reliable information is not available to accurately define this process it was not modelled. Instead, the firefighters were assigned a stair travel speed equivalent to 1.0 min/floor, half that observed in the UK trials for firefighters carrying up to 47 kg of equipment [24] and twice that reported by firefighters in the WTC [23] who were subjected to evacuation contra-flow.

In addition, the model parameter ‘DRIVE’ was set arbitrarily high for each firefighter. Within the software this means that whenever they were involved in a conflict with other people (of lower drive) they would always win the conflict. In effect, this means that building occupants would stand aside and let the firefighter pass each time they vied for space on the stairs. However, once the firefighters have passed, the other occupants would then be free to occupy more of the stair space.

A total of seven different scenarios were run, each scenario being repeated 50 times in order to produce a range of results. The scenarios involved;

- Scenario 1: varying the occupant response time distribution (three cases examined: 1a—response times derived from preliminary HEED analysis [10], 1b—response times based on engineering assumptions (0–2 min) and 1c—instant response times);
- Scenario 1d: investigating the impact of fatigue, response times as in Scenario 1d, travel speeds 80% those of Scenario 1d;
- Scenario 2: investigating the impact of the ascending firefighters on the overall evacuation efficiency, response times as in Scenario 1d;
- Scenario 3: investigating if those occupants trapped above the impact floor could have successfully evacuated had a single staircase survived the impact, response times as in Scenario 1d; and
- Scenario 4: investigating the evacuation dynamics resulting from a full building evacuation involving the full building population, response times as in Scenario 1d.

Summary of evacuation modelling results

The results suggest that the software was capable of reproducing the broad trends in this disaster as they are known. The model predicts the total evacuation time of the building for 8239 survivors — the maximum likely building population—to be approximately *1 h 27 min ± 2 min*, depending on the precise nature of the model assumptions. This time compares favourably with the observation that the building collapsed after some *1 h 42 min* and supports the view that everyone who was able to escape from WTC1 on the day of the incident probably did manage to do so.

The predicted average total evacuation time for Scenarios 1a to 1c varied from a minimum of 53 min 4 s to a maximum of 84 min 33 s (see Table VI). These simulations highlight the importance

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of using a reasonable representation of the response time distribution for high-rise building analysis. Approximating the actual response time distribution using instant or an arbitrarily short response time distribution may result in poor representations of the final phases of the evacuation and unrealistic estimations of the likely total evacuation times. It is therefore essential that a reasonable response time distribution for use in high-rise building applications is developed. It was also noted in heavily congested situations that queues formed on certain floors as the floor occupants were not able to merge with the stair flow. Clearly, if the merging behaviour at floor–stair interfaces is to be correctly modelled, a better understanding of deference behaviour at these interfaces is required.

In an attempt to represent the impact of fatigue on the evacuation dynamics, the maximum unimpeded travel speeds of agents was reduced by 20% from their default values (scenario 1d). In this case, the average total evacuation time increases from 84 min 33 s to 88 min 47 s, an increase of only 5%. Thus the overall evacuation time is not as sensitive to the travel speed variable as perhaps would be expected. However, while arbitrarily reducing the stair travel speeds by 20% did not have a significant impact on the overall evacuation time, it did have an impact on the evolution of the simulated evacuation dynamics, producing reduced exit flow rates throughout the simulation compared to the case with default travel speeds. Furthermore, it should be noted that the impact of reducing the overall agent maximum travel speeds on the total evacuation time may be masked by the higher levels of congestion observed in the simulation with default travel speeds. It is thus essential to derive a better representation of occupant travel speeds on stairs in evacuations from high-rise buildings together with the factors that may impact stair travel speeds such as fatigue.

In the scenario involving the ascending firefighters, the firefighters were inserted into Staircase B (scenario 2). If we consider the evacuation time for those occupants using Staircase B, then we find that their evacuation time is extended from 1 h 21 min 50 s to 1 h 24 min 19 s. Thus the passage of the firefighters in this scenario is predicted to extend the overall evacuation of the occupants using the same stair by 2 min 29 s. The model results thus suggest that while the insertion of the firefighters into the building did impact the evacuation efficiency of individuals, it had minimal detrimental impact on the overall evacuation efficiency of the building.

The model was also used to explore whether those people located above the impact floors could have managed to escape prior to building collapse if at least one stair had remained intact through the impact zone (scenario 3). The model suggests that had Stair B remained intact throughout the building and had the occupants been aware of this, it is possible that an additional 1049 (modelled) survivors trapped above the impact floor could have escaped prolonging the evacuation by approximately *2 min*. These results suggest that had at least one staircase survived from top to bottom, it is possible that everyone who survived the initial trauma of the impact could have managed to safely escape. This underlines the importance of staircase dispersal within buildings. It is essential to make it less likely to lose all means of escape in the event of plausible catastrophic incidents, and that staircases are sufficiently hardened to withstand plausible threats.

Had the building been fully occupied, and using the idealized 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 h 18 min* (scenario 4). This implies that at the time of WTC1 collapse, the expected death toll would be 7492, with some 3108 people caught on the stairs and 4384 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 9/11 scenario would lead to extremely heavy congestion on the stairs leading to a highly inefficient evacuation (see Figure 4). For such a large-scale evacuation it is essential that a balanced distribution (with respect to stair and exit capacity) of people between the staircases is achieved. Evacuation procedures should be developed that attempt to take this into consideration.

The level of evacuation inefficiency/efficiency for a particular floor can be determined from individual agent experience parameters. The evacuation inefficiency for an individual agent is defined as the ratio of the total time spent in congestion during the evacuation to the personal evacuation time for the agent. Thus, evacuation efficiency is simply one minus the evacuation inefficiency.

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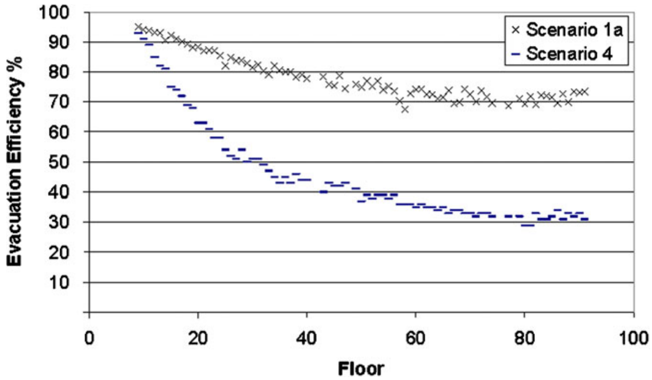

Figure 4. Average floor evacuation efficiency for Scenario 1a (base case, x) and Scenario 4 (21 098 population, –).

The average evacuation efficiency for an entire floor can thus be calculated by determining the average personal evacuation efficiency for all the occupants from a floor.

Generalizing the results from the WTC analysis to high-rise buildings, it is postulated that in high-rise building evacuations, for a given floor population density, the average floor evacuation efficiency generally decreases with height (see Figure 4). However, at a particular height the decrease in evacuation efficiency is arrested and achieves a near steady value with increased building height. Once the critical height has been attained, it is possible to increase the building height without severely compromising the evacuation efficiency of the occupants on the higher floors. As the floor population density is increased, keeping the stair geometry fixed, a critical population density will be reached at which point the achieved steady-state in evacuation efficiency would be nearly zero, effectively capping the maximum height of building that can be practically evacuated via stairs alone. If these results can be demonstrated to be real and not an artefact of the numerical model, they will be significant as they provide a guide to suggesting the maximum building heights that can be practically evacuated by stairs alone.

The findings of project HEED suggests that a significant number of people within the WTC did not evacuate as individuals but as members of groups. The impact that the group dynamic has on occupant response times and evacuation dynamics is poorly understood and as a result poorly represented within simulation models. Work continues to better understand group dynamics and to include this within evacuation models. Finally, while it is possible to represent the reduced movement rates of people with movement disabilities within evacuation simulation, the impact that they may have on the unfolding group dynamics and its impact on evacuation dynamics and hence evacuation models is poorly understood and requires further attention.

CONCLUDING COMMENTS

As part of the UK study into the WTC evacuation, 271 WTC survivors have been interviewed in great detail and data from these interviews have been entered into the HEED database. The main findings from the analysis of the WTC HEED data suggest:

Stoppages:

- From a sample of 124 people in the North Tower (WTC1):
  - 85% of the sample, stopped at least once during their descent in 388 stop incidents.
  - 43% of stoppages were due to congestion while 8% of stoppages were for rest.
  - At least 87% of sample in the Mid and High levels stopped at least once, compared with 75% from low level.
  - 72% of rest stops were incurred by those in the High region.
  - Rest stoppers were: 85% female, 69% overweight+, 62% with medical conditions.

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- BMI and fitness are not predictors of whether a person required a rest stop however; effects may be masked by other types of stoppages providing rest opportunities.

Stair travel speeds:

- Analysis of travel speed data for 30 occupants suggests an average adjusted stair speed of 0.29 m/s, some 45% larger than reported in earlier studies.
- Occupants with stair speeds less than the average speed encountered high levels of congestion for at least 60% of their journey. The lowest recorded speed of 0.17 m/s resulted from an occupant on the 49th floor who encountered high levels of congestion for 94% of their journey.
- It appears reasonable to suggest that the lower than expected stair speeds appear to be affected predominately by high levels of congestion experienced on the stairs for significant periods of time.
- BMI and fitness are not predictors of stair travel speed however, effects may be masked by high levels of congestion encountered.

Response times:

- Response times for 119 people from the North Tower (WTC1) have been estimated.
- Almost 80% of the sample have moderate response times (1–8 min).
- The High region (>60th floor) has the smallest number group of Rapid (<1 min) and Long (>8 min) responders—this is thought to be due to proximity to event.
- On average a person completed four tasks prior to starting to purposefully evacuate.
- Half the sample undertakes three or less tasks prior to evacuating while 9% undertake no tasks.
- Three fifths of the samples undertake up to two *Action Tasks* while three fifths of the samples undertake up to one *Information Seeking Task*.
- On average an *Action Task* required 0.97 min and *Information Seeking Tasks* take 1.6× as long as *Action Tasks.*
- Improving emergency communications could greatly reduce evacuation delays by removing the need to perform *Information Seeking tasks*.
- Improving training could reduce evacuation delays by removing the number of *Action tasks* prior to evacuation.
- Those with a High Perceived Risk responded 1.26× faster than those with Low Perceived Risk.

An important observation to emerge from this study is that BMI and fitness do not appear to be predictors of the need to rest or of stair travel speed. It is believed that high levels of congestion contributed to the low average travel speeds observed in this incident. However, the impact of BMI and fitness may be masked by the high levels of congestion.

Computer Modelling: The computer modelling analysis of the evacuation of the WTC resulted in a series of important findings relevant not only to the particular circumstances of 9/11, but to high-rise buildings in general and to identifying areas in human factors and evacuation modelling technology requiring further research and development. The key conclusions from this study are:

- The predicted evacuation time for 8239 survivors in the North Tower of the WTC is approximately *1 h 27 min ± 2 min*, depending on the precise nature of the model assumptions.
    - This time compares favourably with the observation that the building collapsed after some *1 h 42 min* and supports the view that everyone who was able to escape from WTC1 on the day of the incident probably did manage to do so.
- The simulations of the North Tower evacuation suggest that while the insertion of firefighters into the building did impact the evacuation efficiency of individuals, it had minimal detrimental impact on the overall evacuation efficiency of the building.
- The simulations of the North Tower evacuation suggest that had Stair B remained intact throughout the building it is possible that all 1049 survivors trapped above the impact floor could have escaped, extending the evacuation by only approximately 2 min.

  - This underlines the importance of staircase dispersal within buildings. It is essential to make it less likely to lose all means of escape in the event of plausible catastrophic incidents, and that staircases are sufficiently hardened to withstand plausible threats.
- In the simulations of the North Tower evacuation, arbitrarily reducing agent maximum stair travel speeds by 20% to represent fatigue reduced overall evacuation times by only 5%. However, this had a significant impact on the overall evolution of the evacuation dynamics, producing reduced the exit flow rates throughout the simulation and reduced levels of congestion compared with the case with default travel speeds.
  - It is thus essential to derive a better representation of occupant travel speeds on stairs and factors such as fatigue which may impact stair travel speeds in evacuations from high-rise buildings.
- Had the North Tower of the WTC been fully occupied (25 482 occupants) the predicted time required to evacuate the building is estimated to be approximately *2 h 18 min*. This suggests that at the time of WTC1 collapse, the expected death toll would be 7492, with some 3108 people caught on the stairs and 4384 people either killed in the impact or caught above the 91st floor.
  - A mass evacuation of a fully occupied building in a 9/11 scenario would lead to extremely heavy congestion on the stairs leading to a highly inefficient evacuation. In such cases it is essential that a balanced distribution (with respect to stair and exit capacity) of people between the staircases is achieved. Evacuation procedures should be developed that attempt to take this into consideration.
- For high-rise building evacuation simulations, the predicted average total evacuation time is strongly dependent on the nature of the response time distribution imposed on the simulations.
  - These simulations highlight the importance of using a realistic representation of the response time distribution for high-rise building evacuation analysis.
- For high-rise building evacuation simulations involving heavy congestion, queues form on floors as the floor occupants are unable to merge with the stair flow.
  - If the merging behaviour at floor–stair interfaces is to be correctly modelled, a better understanding of deference behaviour at these interfaces is required.
- In high-rise building evacuations, the impact that group dynamics has on occupant response times and evacuation dynamics is poorly understood and as a result poorly represented within simulation models.
  - Further research work is required to better understand group dynamics and to include this within evacuation models. Also, the impact that people with reduced mobility have on the unfolding group dynamics and its impact on evacuation dynamics and hence evacuation modelling is poorly understood and requires further attention.
- The computer simulation analysis suggests that for a given high-rise building configuration and floor population density, as the number of floors increase the average floor evacuation efficiency decreases with height until a steady-state is reached. Once the steady-state is attained, additional floors above the threshold floor do not incur significant further degradation in evacuation efficiency.
  - More generally, as floor population density increases, keeping stair geometry fixed, a critical population density will be reached at which point the achieved steady-state in evacuation efficiency would be nearly zero, effectively capping the maximum height of building that can be practically evacuated via stairs alone.

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