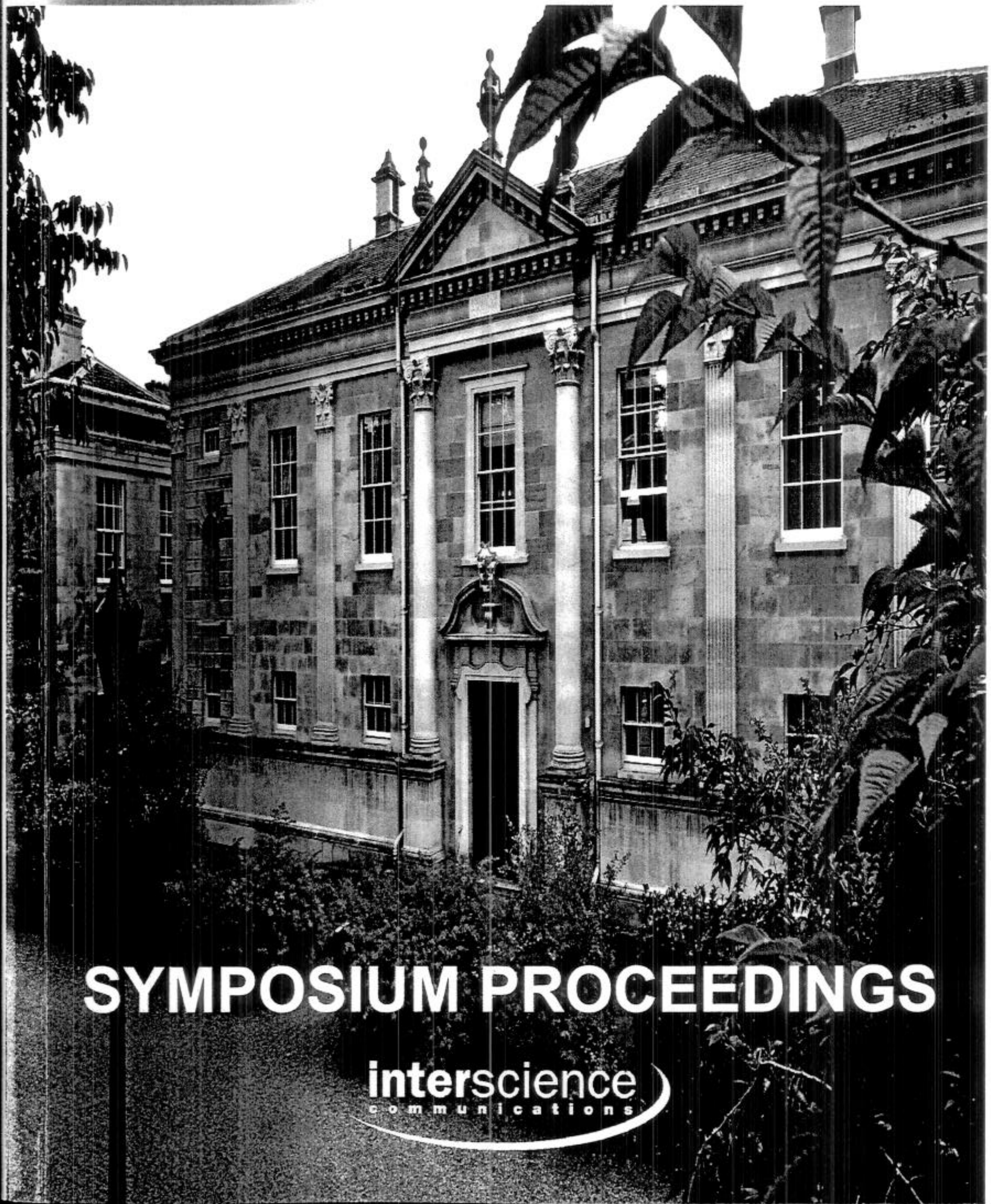
5th international Symposium

Human Behaviour in Fire 2012

Downing College, Cambridge, UK | **19th - 21st September 2012**



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INTRODUCTION

It gives me very great pleasure to welcome you all to this the 5^{th} international symposium on Human Behaviour in Fire. Since the symposia's inception in 1998 we have directly influenced many changes and been prominent in the development of fire safety engineering. We see colleagues make career changes and sadly some are taken from us. All the more reason then to make the most of our time here together, to network and catch up with old friends and colleagues. Remember at this symposium there are no strangers here only friends waiting to be introduced.

The Programme Committee have selected a cross section of papers to stimulate the mind and hopefully the organisers will include some moments in the social programme to stimulate the senses! Some 43 technical papers and 14 poster papers are included along with Panel Discussions and Workshops on:-

- Life Safety Options for People with Disabilities - How far have we come? - Implications of Our Aging Society on Design and Management of Buildings
- Fundamentals of Egress Calculations for Life Safety Assessment
- Workshop on the Ethics of Behavioural Studies

As we approach the 5th symposium there many big issues to be addressed. For example, where exactly are we, in human behaviour terms, with respect to fire safety engineering and performance based design? Given our well established foundations what should be our focussing on for the next decade? These issues will be addressed at the symposium and your active partition in discussions surrounding them is eagerly anticipated.

I hope you will enjoy the next 3-4 days and like me, make the most of your time here in the fine surroundings of Downing College, Cambridge.

Prof. T Jim Shields

Symposium Chair

THE COLLECTION AND ANALYSIS OF DATA FROM A FATAL LARGE-SCALE CROWD INCIDENT

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ABSTRACT

This paper discusses the analysis of data-sets from observations made at the Duisburg Love Parade in 2010 and the large-scale crowd situation that ended in fatalities due to the development of crush conditions. This event is a useful case study of large crowd circulation based on the material that was made publically available by the organisers and attendees. The resultant data-set has been used to configure the buildingEXODUS model to approximate the original incident in order to verify both the model's performance and the underlying scenario assumptions; i.e. whether buildingEXODUS can reliably represent agent actions, the conditions that develop and the impact of these developments.

INTRODUCTION

Simulation tools are frequently used to predict pedestrian and evacuee performance in large crowds. These crowds can form for a number of reasons, by a range of different people, who exhibit a variety of different behaviours. The features of the event area, the nature of the event as well as the size, nature and constitution of the crowds influence the type of situations that can arise and the conditions that are produced. These situations can range from benign incidents to events resulting in the large-scale loss of life [1]. The accuracy and reliability of the simulation tools used to represent such events is dependent upon their ability to qualitatively and quantitatively capture the outcome of the performance of the individuals that make up the crowd; i.e. whether they can reliably represent agent actions, the conditions that develop and the impact of these developments [2]. This paper discusses the analysis of a large-scale crowd situation that ended in fatalities due to crush conditions. The resultant data-set was used to configure the buildingEXODUS model [2,3] in order to simulate a comparable incident and determine whether a model such as this could be used to predict the on-set of hazardous crowd conditions.

The 2010 Duisburg Love Parade was selected for analysis and information concerning this incident was gathered primarily by examining the original video footage [4]. This event produced a bidirectional flow and extremely high population densities in key areas. Procedural measures were taken in an effort to prevent the situation from worsening; however, the conditions ultimately led to 21 fatalities and approximately 500 injuries [5].

People movement within an area occurs in highly coupled phases. Gwynne and Kuligowski characterised these phases into a people movement system 6 and emphasised the importance of treating people movement as a single system that can exist in a number of states, rather than as a number of unrelated entities; therefore, the routine circulation movement prior to the incident can be a key contributor to the way that the incident unfolds. In this paper, the transition from routine movement to a potential large-scale incident is modelled using buildingEXODUS. The initial conditions prior to the crowd incident are modelled to demonstrate that the software is capable of modelling the initial conditions in a realistic and credible manner.

buildingEXODUS 2[3] is a fine mesh model; i.e. the geometry is constructed from a set of homogenous nodes each of which can be occupied by one person at a time. Traditionally, fine mesh models are not normally used to investigate extremely high-density crowd situations since the models are constrained

by their underlying discretisation of space which limits the maximum crowd density that can be represented. In this paper, a novel approach is introduced to combine the performance data of pedestrian flow and space utilisation to indicate the onset of potentially dangerous population densities using a fine node model. This allows the predicted and observed results to be compared directly.

A scenario that incorporated similar conditions to those of the Love Parade was created based on the information derived from video footage of the original incident. A crowd of approximately 28,000 was represented within the buildingEXODUS model; the individuals were simulated as arriving and moving in accordance with the observations made. Crowd management measures implemented by the authorities during the Love Parade incident, such as the setting up and consequent dissolving of several police cordons, were also represented in the model to simulate the impact of these measures on the flow and build-up of population in a specified area.

THE LOVE PARADE

Origins

The Love Parade (LP) started with a group of 150 people at the 1989 opening event in Berlin 7 and continued to grow in popularity and visitor numbers. Access to the 2010 parade was free and unmanaged and, as a result, accurate numbers are not available. Estimates 8 of visitor numbers to the parades prior to 2010 are more than 1 million people.

The area

The German city of Duisburg was granted permission to host the 2010 LP. The designated festival grounds were a disused train depot of approximately 110,000 m^2. City officials and the event organisers calculated that a maximum of 250,000 visitors at any given time would be able to make use of the grounds 8. Figure 1 presents an overview of the festival grounds.

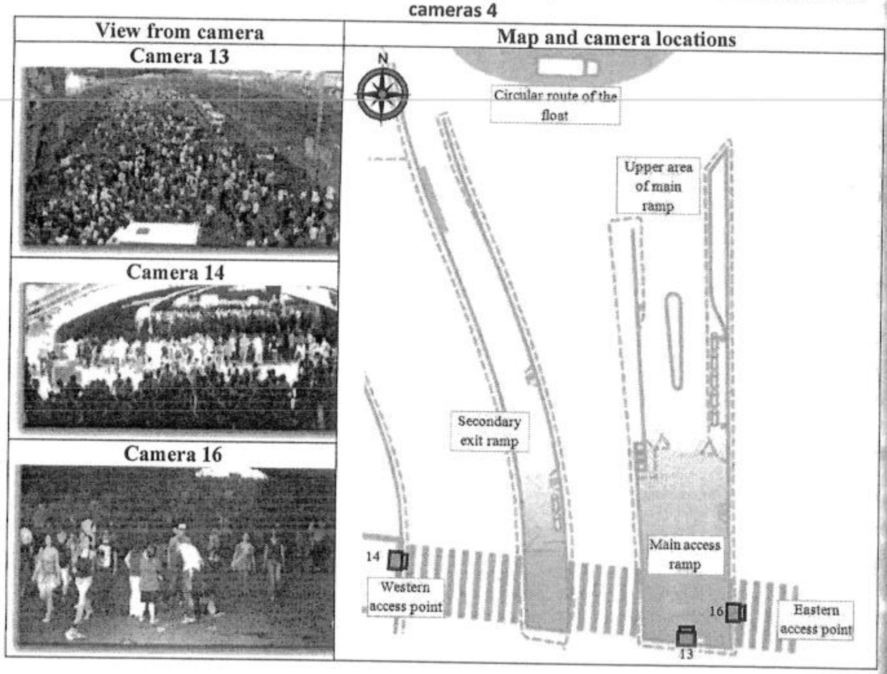
A single access ramp leads from Karl-Lehr Street to an area that was designated for the festival's float parade. The float parade, a convoy of large trucks with disc jockey stations, followed a circular route around the disused buildings of the train depot. A stage that was to be used for the main event of the day was constructed on the northern side of the depot buildings and consequentially hidden from view of those on the main access ramp.

Visitors entered the festival grounds at control points on the western and eastern side of the grounds (see Figure 1). The route took visitors through a series of tunnels or underpasses before reaching the single access point: the base of the main access ramp. From here, visitors made their way to the main festival area. The main ramp was used by visitors entering and leaving the site, as well as emergency and police vehicles.

The 2010 Love Parade Crowd Incident

On 24 July 2010 the LP opened an hour late due to last-minute work on the site [9,10], resulting in the build-up of crowds prior to their entrance to the site. Officials confirmed that 105,000 people had arrived by train between 9:00 and 14:00[11]. Video evidence shows a large number of people already in the festival grounds about an hour after the parade had started. Visitors were able to ingress and egress from the site using all of the routes available. The video footage of the upper area of the ramp does not appear to contain evidence of clear signposting to guide visitors to the main stage area. It was also not apparent whether crowd officials encouraged the visitors to move around to the main area of the event. This is supported by eyewitness accounts in the media[10,12]. The upper area of the main access ramp became densely populated as visitors gathered in this area, impeding the flow of those travelling in the direction of the float route and stage.

Figure 1: Map identifying secondary ramp, main entry ramp and location and views of the CCTV cameras 4

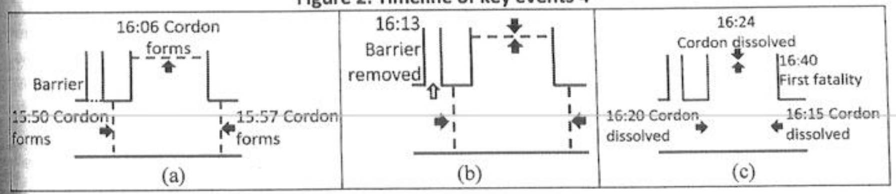


The small ramp (designated as a secondary exit (see Figure 1)), did not appear to have been clearly signposted and in the footage analysed it is evident that relatively few people used this route to leave the area. Instead, visitors used the same route to leave that they had used to enter the festival area; i.e. the main ramp. This behaviour was also observed by the crowd manager 9 and is consistent with the prevailing pedestrian and evacuation theory that states that people tend to move towards exit points which they have previously used [13,14,15].

By 15:30 some visitors started scrambling up the steep, grassy embankments in an attempt to move around the crowd that had formed at the upper area of the ramp. Some revellers reported afterwards that, due to the overcrowding, they did not want to stay at the festival and started to make their way home early [10,12]. The decision was made to use police cordons in an effort to halt the flow of people into the site so as to prevent the conditions worsening 1. Therefore, noting that congestion was developing at the north end of the ramp, cordons were put in place to reduce the unmanaged flow. The timeline of the key events are presented in Figure 2.

Once the police cordons had dissolved, the pent-up flow of arrivals met those leaving the parade ring head-on around the location of the former main ramp cordon. The conflicting flow led to increased forces on those at or around the original cordon on the main ramp, with little opportunity to move to a place of safety. This led to 21 fatalities, mainly near the original site of the main ramp cordon.

Figure 2: Timeline of key events 4



DATA COLLECTION

In this section, the collection and subsequent analysis of the data are discussed. The resultant data-set was used to configure the buildingEXODUS model in order to simulate the underlying flow characteristics of the event and represent a comparable incident.

Areas

Video evidence of the 2010 LP showed fluctuating and complex flow patterns during the course of the day. The flow patterns in three key areas (see Figure 1) were examined allowing an understanding of the flow patterns evident and the resultant conditions produced. Areas covered by cameras 14 and 16 were selected based on the fact that all visitors entering or leaving the festival area had to pass these points. The third area, filmed by camera 13, was chosen since this was the area where the flow from the two entry points merged and where the critical conditions emerged. This was also the area where fatalities occurred due to the crush conditions that developed.

The section that follows discusses additional factors that were considered for the selection of the footage and the setting up of regions to record the number of visitors.

Factors considered for choosing Data Collection areas

Following the selection of suitable CCTV footage, the dimensions of the data recording area had to be estimated. The exact height of the CCTV cameras was not known and the travel speed of the visitors was used to help determine a data-recording region. Video editing software was used to extract the data and, where necessary, to improve the quality of the footage.

Data collection regions were specified in the western and eastern underpasses. The specified region in the western underpass is presented in Figure 3. The assumption was made that people who were travelling away from the camera were heading towards the festival area and those travelling towards the camera were leaving the area. In Figure 3(a) two people are inside the region and were counted and their direction of travel noted. In Figure 3(b) 10 seconds have elapsed and the same two people are now outside the region.

Figure 3: Specified data collection region in the western underpass (CCTV source 4)

(a): Person x

(b): Person x + 10s

For the main entrance region, the area north of the narrowest part of the ramp was used to record the flow (see Figure 4). This area was selected because it showed less congestion than the area closer to the camera, at the narrowest point of the ramp. This camera was further away from the area that it was filming (compared to cameras 14 and 16). A region that took 10 seconds to cross (consistent with the previous methods) proved difficult to count due to the small size of the image. As a result, a location was specified for data collection and a people count was performed at 2-second intervals.

Figure 4: Camera 13 - Main entrance / exit ramp (CCTV Source [4])

A summary of key events and the observed flow rates is shown in Table 1.

Table 1: Measured flow rates at key event times

Time	Location	Event	Estimated flow rates (ppm)	
			Arrivals	Departures
15:50	Western tunnel / underpass	Police cordon forms	287	85
15:57	Eastern tunnel / underpass	Police cordon forms	110	157
16:06	Main access ramp	Police cordon forms	203	*197
16:13	Secondary, exit ramp	Barrier is removed to allow people in the Western tunnel to enter the festival area	194	*197
16:15	Eastern tunnel / underpass	Cordon dissolves	200	*197
16:20	Western tunnel / underpass	Cordon dissolves	322	*197
16:24	Main access ramp	Police Cordon dissolves	275	*197
16:40	Main access ramp	Estimated time of first fatality 4	*264	*197

* Values based on the average flow rate observed in the few minutes before congestion impeded the flow rate

In addition to these flow estimates, stills were extracted from the footage allowing a timeline of key conditions to be developed. These were used in the development of an event timeline that allowed the simulated and observed (qualitative) conditions to be compared.

METHODOLOGY

Modelling overview

Several evacuation models are available for reproducing crowd incidents, each with unique characteristics. However, evacuation models do not routinely have the capability of representing circulation behaviour. When emergencies occur in large crowd events which may trigger an evacuation, parts of the crowd remote from the incident may be unaware of the evacuation and continue circulating. Given this, circulation behaviour may both directly inform the initial conditions of the evacuation, and also potentially form a significant portion of the behaviours exhibited during an evacuation. buildingEXODUS is capable of modelling non-emergency circulation behaviour and the new arrival of pedestrians before and during an emergency incident. Features include, but are not limited to, occupants with imposed tasks, occupants arriving during the incident, complex flow patterns and route availability (i.e. routes / exits that can be configured to open or close at specified

times). These features can be useful for representing crowd circulation behaviour and can provide insight into exit usage, population distribution, congestion, etc. 2[3].

This section describes the key assumptions and model parameters used in the analysis of the LP incident. In conjunction with the spatial and procedural constraints present, the overloading of pedestrian routes can quickly lead to serious crowd incidents, such as those observed at Hillsborough [16], the Station Nightclub fire [17], the Hajj [2] and, of course, the Duisburg Love Parade [4]. Several pertinent factors were present on the day of the Duisburg LP tragedy [4]. Large numbers of visitors arrived for a festival in a relatively short period of time. They shared the relatively confined space of the path into the site with emergency vehicles and people travelling in the opposite direction i.e. leaving the event. This was a popular event and yet neither the number of visitors nor the population flow appeared to be managed adequately. Instead, in an effort to remedy a worsening situation, the authorities implemented a series of mitigation actions in a hope to defuse what was already challenging circumstances.

The effects of the crowd management procedures deployed on the day of the incident are examined. This is to assess the effectiveness of the buildingEXODUS model at representing such incidents and, subsequently, gain some insight into the key factors of the incident itself. We briefly discuss the probable outcome if the police had not taken action to stop conditions from worsening in a key location.

The buildingEXODUS evacuation model

buildingEXODUS is an evacuation modelling package developed by the Fire and Safety Engineering Group (FSEG) at the University of Greenwich [2,3]. The model is designed to simulate the circulation and evacuation of large numbers of people from complex structures. The model comprises five core interacting sub-models: the Occupant, Movement, Behaviour, Toxicity and Hazard sub-models. The software is rule-based, with the progressive motion and behaviour of each individual being determined by a set of heuristics or rules. Architectural plans can be loaded straight in to the simulation suite to represent the structure or the user may avail themselves of a number of interactive design tools. On the basis of an individual's personal attributes, the Behaviour Sub-model determines the occupant's response to the current situation, and passes its decision on to the Movement Sub-model.

buildingEXODUS has several features that makes it suitable for the modelling of circulation behaviour. Some features enable the user to impose specific behaviours on the population, such as the assignment of itineraries, while other features allows the user to collect data in areas of interest without interfering with the behaviour of occupants (i.e. establish the impact of the behaviours represented upon performance). The software has been used to model other external large crowd situations such as for the Beijing Olympics and more recently for the Hajj 2. The model functions identified have been used to simulate a series of different procedural measures, ranging from the setting up of police cordons at specified times and at specified points, to creating complex flow patterns.

Scenario description

A geometry was produced to represent the main ramp and the adjoining access routes within the buildingEXODUS model. The simulated area included those areas described by the CCTV footage, the main access and egress routes, the locations of the key events during the incident and the areas of procedural interest.

A case with similar conditions to those of the LP was created based on the information derived from CCTV footage of the original incident. The observed flow of visitors and crowd management measures were represented in the model; e.g. the setting up and consequent dissolving of several police cordons. The starting point of the scenario was two minutes before the first police cordon formed (15:48), using the arrival and departure rate that was recorded from the actual footage. The number and distribution of people within the area modelled at the start time of the simulation was also estimated. The scenario was simulated over 52 min focusing on the main entrance region. During the 52 min, arriving and departing visitors shared the same routes. During the original incident, after arrival, visitors passed into the parade area and then left after a period of time. During the course of the day, the bidirectional flow of visitors increased and crowd officials decided to deploy crowd management measures, including the use of police cordons, to deliberately halt the flows into and out of the site. High population densities developed as the bidirectional flow met in a relatively confined space on the main access ramp and ultimately led to fatalities.

Analytical approach

The measured results from a real incident are typically used as a basis of comparison with predicted results. However, given that the LP was not an evacuation but a crush incident, there were fewer numerical indicators available for comparisons to be made (in terms of the movement and actions of pedestrians and evacuees, times to reach safety, clear an area, etc.). As such, measures had to be developed to (1) identify criteria that might indicate that crush conditions may develop and (2) allow potential crush conditions to be identified within a simulation. These then allowed qualitative comparisons to be made between the simulated and observed conditions. The process of developing and employing these measures are now described.

Establishing crush conditions

Crowd incidents such as those witnessed at Hillsborough [16] are testament to the fatal force levels that can emerge within high-density crowds when procedures are questionable, physical constraints are present, routes are overloaded, and/or information is not disseminated to all the members of the crowd. Some evacuation models attempt to model the occurrence of crush [18]. However, models that factor in the physical forces within a crowd will typically employ computationally expensive calculations. High-level techniques to establish the onset of crush conditions have been explored, such as the early warning method for crush considered by Harding [19].

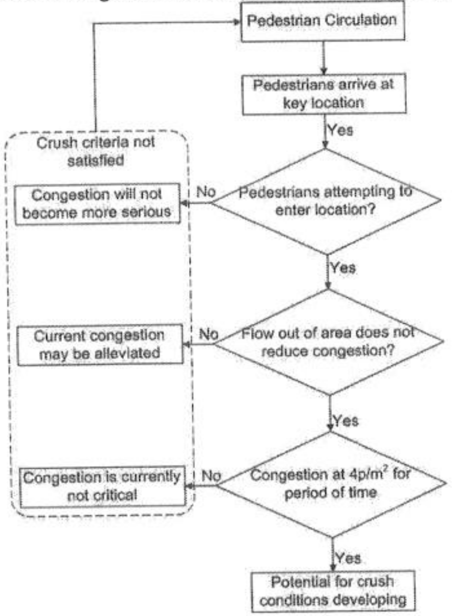
Given that the buildingEXODUS model employs a nodal mesh, constraining the population densities that can be simulated, a method was required to establish when crush conditions are likely to occur, rather than making an explicit attempt at predicting such conditions. In the current method, no functionality has been added to the model. Instead, post-processor analytical techniques have been developed to estimate when the prevailing conditions suggest that crush conditions may develop. As such, a higher-level assessment has been made to determine when conditions may become critical rather than establishing individual exposure to the forces from the surrounding population.

Several pieces of empirical work have been examined [1,20,21] that indicate that an individual's movement becomes constrained by the developing crowd at a population density of approximately 4.0 p/m^2. Using this information as a necessary prerequisite, a set of precursors have been identified that suggest that hazardous conditions may be developing within a crowd that may lead to the development of crush conditions:

(PC1) ***Elevated Density Achieved:*** A population density of 4 p/m^2 is achieved within the model (see Figure 5). For crush injuries to be possible, this population density must first be reached.
(PC2) ***Extent of Density:*** The elevated density is not localised to a small region of space occupied by only a small number of people, but spread across a large portion of the geometry. For instance, in areas adjacent to the presence of blockages or cordons (i.e. where flow was unexpectedly stopped). This criterion is met if elevated densities spread across an entire zone of interest.
(PC3) ***Continuing Arrivals:*** People continue / attempt to arrive into this area. This criterion is met if a reservoir of people is present in an adjacent zone that intends to enter the zone.
(PC4) ***Insufficient Departures:*** Flow out of the area does not reduce the population density within the area, i.e. no net reduction in zone density. This criterion is met if the numbers able to leave the zone does not result in a net change in the population density of the zone. This can occur if the neighbouring region, in the intended direction of movement is also fully occupied.
(PC5) ***Persistence of Elevated Density:*** Compressive asphyxia can occur when critical crowd crush conditions persist for an extended period of time. Typically, asphyxia occurs after 3 min of oxygen deprivation, at which point unconsciousness (or worse) may be expected [23]. However, the maximum population density that can be represented within the model is 4p/m^2 - a level at which compressive asphyxia is unlikely to occur. A time is then required to represent the potential escalation of the density conditions above densities of 4p/m^2 to densities in excess of 6 p/m^2 at which point injury is possible. Given that precursor conditions PC1 to PC4 are present, an overall threshold of 5 min is adopted to represent the potential increase of the population density to dangerous levels and then the compression of individuals within the crowd such that asphyxia (unconsciousness) may occur. Thus, if conditions PC1 to PC4 occur, a crowd subjected to these conditions for 5 min or more, is considered to be vulnerable to injuries due to compressive asphyxia. Note, other types of injuries are not addressed.

Based on these simple precursors, an analytical process was developed (see Figure 5) to establish whether crush conditions might potentially arise - whether congestion of sufficient scale, level and persistence was produced. These factors are expected to lead to areas of maximum density and then escalate the forces felt by the simulated population, potentially exposing them to crush conditions.

Figure 5: Establishing whether congestion has the potential for hazardous conditions to develop

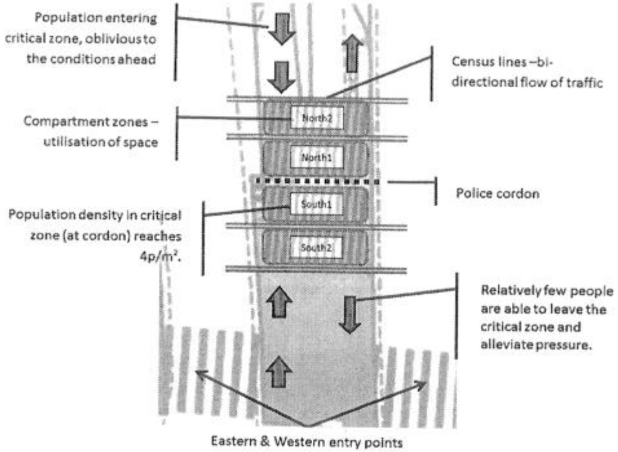


A series of measures were taken within the buildingEXODUS model to identify whether these criterion were met during the simulation: if they occurred (exclusively) in the vicinity of the fatalities in the original incident, and if they occurred at approximately the same time; in effect, if the model is able to produce comparable conditions that might generate the fatalities observed and therefore be able to discriminate between situations where crush fatalities may or may not occur.

In the scenario, two main regions of interest were identified where the police cordon formed on the main ramp and data was collected on the utilisation of this space, the North 1 and South 1 regions in Figure 6. The regions neighbouring these two main regions, North 2 and South 2 were also monitored as the population entering/leaving the main regions (North1 and South1) would be influenced by the movement of people from these regions (i.e. North2 and South2). The arrivals and departures from each section were recorded, thus establishing flow patterns (see Figure 6). This formed the primary area of interest, as comparisons could be made with the deteriorating conditions evident during the original event.

The data enabled the authors to establish whether the five underlying precursors (PC1 to PC5) were met during the scenario and when these were met. This allowed an estimate of when a maximum simulated level of density was reached (i.e. 4 p/m^2), the period of time over which it existed, whether a large reservoir of people were in the adjacent zones and were attempting to move into the zone of interest, and whether the population in the zones were able to move off, alleviating any pressure building up.

Figure 6: Primary areas identified for data collection



Observations were then focused on the key areas where the conditions deteriorated during the original incident by identifying zones of interest and establishing the associated flow rates and population levels as the incident progressed – both to compare the conditions produced and then gain some insight into the original incident.

The area where the main ramp met the parade floats was also examined in order to establish whether the original area of concern that led to the formation of the cordons during incident (i.e. congestion at the entrance of the float parade) was produced during the simulations. A scenario that represented the flow rates that was observed on the day of the incident were modelled and showed that, without the police cordons, the population density in the upper ramp area would have exceeded 4 p/m^2 by 15:55.

Using the Event Timeline

Numerical and visual comparisons were made between the simulated and observed results. These specifically related to the congestion that formed in key areas of the site and when this occurred. This approach was adopted to compensate for the lack of definitive performance milestones extracted from the original observations, given the nature of the event. Timeline' narratives were produced by extracting stills from the original video footage and comparing them with output provided by the buildingEXODUS simulation. A visual comparison is presented in Table 2.

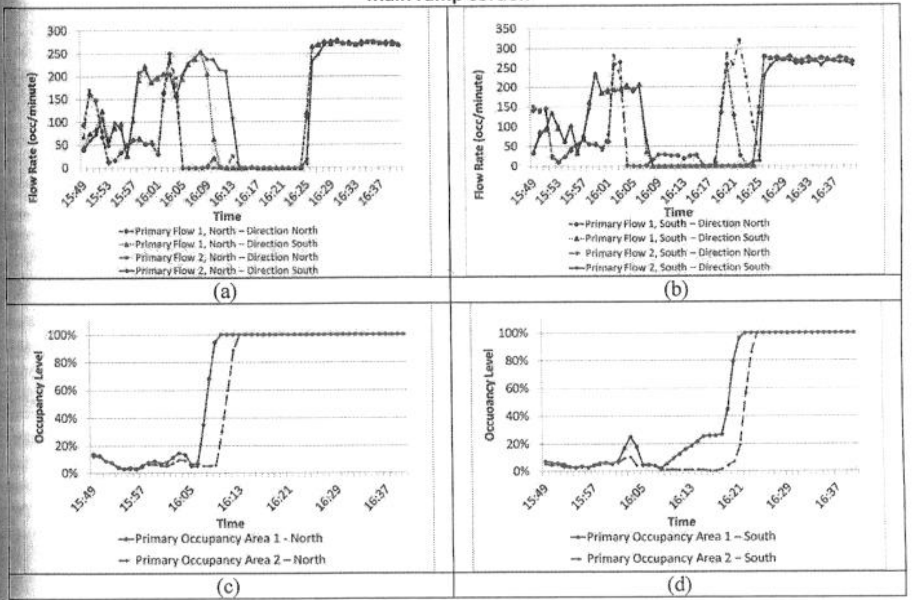
The key qualitative conditions that had been visually highlighted were then cross-referenced with the numerical data produced – either from the derived flow rates or from the simulated conditions produced at various locations within the geometry. This allowed results to be examined to establish whether acceptable quantitative conditions were produced in conjunction with the qualitative crowd formations, at the appropriate time.

RESULTS AND DISCUSSION

In this section, we discuss the application of the buildingEXODUS software to the large-scale crowd situation presented. We have attempted to reproduce a situation similar to the LP incident, informed by the data sets collected from the footage of the original incident. The key elements represented included the crowd management measures that were deployed, direction of the flow, derived from flow rates and the utilisation of space.

In an attempt to set up a representative situation, the recorded arrival and departure rate observed shortly before the first police cordon formed was used to configure the initial pedestrian movement. The first cordon formed at 15:50 and at this point the observed flow rate was approximately 90 ppm moving south (leaving the site) and 270 ppm travelling north (arriving). The observed flow rates were represented in the model and the results of the simulated flow rate are presented in Figure 7.

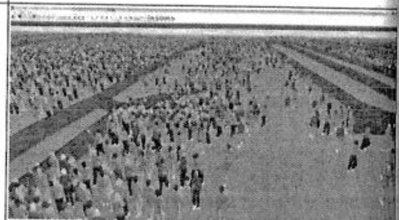
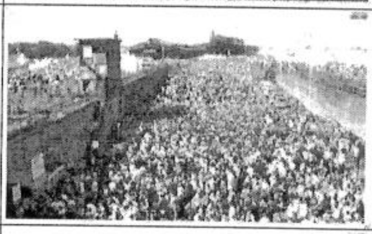
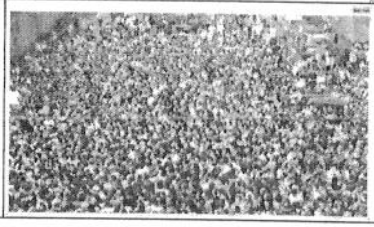
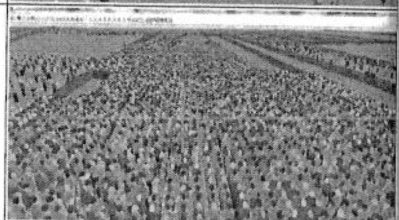
Figure 7: Performance data – simualted flow rates (a and b) and occupancy levels (c and d) at the main ramp cordon



It is apparent that the simulated flow levels produced are either low or counteract each other; the flow into and out of the key zones have little net impact on the occupancy levels and therefore prolonged the congestion levels measured. The simulated result is presented in Figure 7c and d. It is apparent that all four areas where fully occupied after 16:25 and had a population density of 4p/m^2 for significantly longer than five minutes. These conditions then meet the five criteria identified as indicating the development of hazardous conditions which could potentially result in a crush. Importantly, given that the model was configured in accordance with the observed flow conditions, it produced representative outcomes.

The event timeline of the simulated and observed events demonstrated that the model produced comparable qualitative results to those observed in the footage at the specified locations and at the expected times (see Table 2). The simulated areas that were monitored on the main ramp reached 100% of their capacity at approximately the same time that the footage showed high densities in the same area. The original footage showed that the area on the northern side of the ramp reached high population densities before the area on the southern side of the ramp and this was echoed in the simulation. It is evident from original police footage [22] that there was an uneven distribution of people within the site – some areas were unoccupied while others showed a high population density. The only prolonged areas of severe congestion during the original incident were at the cordons, with critical congestion only occurring at the cordon on the main ramp and the upper part of the main ramp as it joined the parade circle. Importantly, the simulation was able to capture this situation: the only critical levels of congestion produced were at the cordon on the main ramp, with secondary and temporary levels of congestion produced at the upper ramp area. The model was broadly able to represent the qualitative conditions observed on the data at similar locations at the same points in time.

Table 2: Timeline – comparison of the conditions on the main access area (Video stills source [4])

Time	Sim (s)	Event	CCTV Footage[4]	Simulation
16:02	720s (14 mins)			
16:20	1,920s (32mins)	*W.Pol.Cordon dissolves*		
16:39	3,060s (51mins)			

CONCLUDING COMMENTS

A novel approach has been presented in order to combine pedestrian flow data and space utilisation to simulate the development and onset of potentially dangerous population densities, using a fine node model. The model was used to approximate the original incident in order to verify both the model's ability to represent the scenario and the scenario assumptions. When representative assumptions were made, the model was broadly able to capture key crowd features and suggest causal factors. A visual comparison of conditions on the main access ramp bore resemblance to the events that took place in the actual incident. Opposing flows that met in the confined space on the main ramp resulted in congestion and the configured model correctly demonstrated that visitors experienced severe congestion in this area. The buildingEXODUS model proved capable of representing a range of individual behaviours in a crowd of approximately 28,000 people. This led to credible emergent conditions being produced.

The adopted approach had a number of limitations that may have affected the accuracy of the derived findings, given factors that were not modelled. These factors include the varying densities in the upper ramp area (due to the effects of the floats moving through the crowds) and low-level activities (e.g. visitors escaping by means of a small staircase). The representation of more fundamental crowd activities is left for future work.

REFERENCES

1 Fruin, J.J., 1993. "The causes and prevention of crowd disasters.", First International Conference on Engineering for Crowd Safety. Eds: Smith, R.A. and Dickie J.F., Elsevier, ISBN 0444899200

2 Siddiqui,A.A., Gwynne, S.M.V., 2012. "Employing pedestrian observations in engineering analysis" Safety Science, Volume 50, Issue 3, Pages 478–493. doi: 10.1016/j.ssci.2011.10.011.

3 Galea, E.R., Sharp, G., Lawrence, P., 2008. "Investigating the Representation of Merging Behavior at the Floor Stair Interface in Computer Simulations of Multi-Floor Building Evacuations". Journal of Fire Protection Engineering, Vol18, pp. 291-316. Publisher SAGE.

4 Lopavent GmbH, 2010. "Love Parade". [Online] http://www.dokumentation-loveparade.com [Accessed February 2011].

5 Ackermann, O., Lahm, A., Pfohl, M., Köther, B., Lian, T., Kutzer, A., Weber, M., Marx, F., Vogel, T., Hax, P.,"Patient Care at the 2010 Love Parade", Deutsches Ärzteblatt Int. 2011, 483-489.

6 Gwynne, S.M., Kuligowski, E.D., 2009 "Simulating a Building as a People Movement System.", Journal of Fire Sciences, v27, pp343-368. DOI: 10.1177/0734904109102387

7 Roeingh, M., "Das Gefühl von 03:30 Uhr in einem Berliner Club…." [Online] www.drmotte.de [Accessed July 2011].

8 Diehl, J., "Maximum Capacity of Love Parade Site Was Just 250,000." [Online] http://www.spiegel.de/international/germany/0,1518,708462,00.html [Accessed Jan 2011].

9 Bönisch, G., Röbel, S., "Interview with the Love Parade Crowd Manager." [Online] http://www.spiegel.de/international/germany/0,1518,711099-2,00.html [Accessed February 2011].

10 Bild, "How the deadly Love Parade disaster unfolded." [Online] http://www.bild.de/news/bild-english/news/how-the-love-parade-disaster-unfolded-13422954.bild.html [Accessed January 2011].

11 Mara, D., Levitz, D., "Prosecutors launch investigation into Love Parade tragedy." [Online] http://www.dw-world.de/dw/article/0,5835760,00.html [Accessed January 2011].

12 Becker, S., Bönisch, G., Brandt, A., Dallkamp, J., Kneip, A., Müller, M., Rapp, T., Röbel, S., Scheuermann, C. "Looking for Answers in Duisburg." [Online] http://www.spiegel.de/international/germany/0,1518,709763-2,00.html [Accessed February 2011].

13 Gwynne, S.M., Galea, E.R., Owen, M., and Lawrence, P.J., 1999. "Escape As A Social Response." Report Published by the Society of Fire Protection Engineers, USA.

14 Donald, I., Canter, D., 1990 "Behavioural Aspects of the King's Cross Disaster", Fires and Human Behaviour 2nd Ed., New York: John Wiley and Sons.

15 Sime, J., 1992. "Human Behaviour in Fires:Summary Report". Portsmouth Polytechnic.

16 Taylor, J., 1989. "The Hillsborough Stadium Disaster; Inquiry; HMSO". London.

17 Grosshandler, W., Bryner, N., Madrzykowski, D., Kuntz, K., 2005. "Report of the Technical Investigation of the Station Nightclub fire". National Institute of Standards and Technology.

18 Helbing, D., Molnar, P., Farkas, I., Bolay, K., 2001. "Self-organizing pedestrian movement". Environment and Planning B: Planning and Design, p361-383.

19 Harding, P.J., Gwynne, S.M. and Amos, M., 2010."An early warning method for crush". Computing, p.1-14. [Online] http://arxiv.org/abs/1008.2160 [Accessed May 2010].

20 Kholshevnikov, V., Samoshin, D., 2008 "Laws of Motion of Pedestrian Flow-Basics for Evacuation Modeling and Management". NATO Science for Peace and Security Series C, 417-442.

21 Nelson, H.E., Mowrer, F.W, 2002. "Emergency Movement.", The SFPE Handbook of Fire Protection Engineering. Third ed., pp. 3-367-3-380. Eds: P.J.DiNenno and W. D. Walton. Bethesda, MD: Society of Fire Protection Engineers.

22 Bönisch, G., Brandt, A., Röbel, S., "Testimony Reveals Police Role in Love Parade Disaster". [Online] http://www.spiegel.de/international/germany/0,1518,776439,00.html [Accessed 03/11].

23 Personal communication with Dr M.V.P.Gwynne MB BS.