Investigating the Representation of Merging Behavior at the Floor–Stair Interface in Computer Simulations of Multi-Floor Building Evacuations

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ABSTRACT: In this article, the representation of the merging process at the floor–stair interface is examined within a comprehensive evacuation model and trends found in experimental data are compared with model predictions. The analysis suggests that the representation of floor–stair merging within the comprehensive model appears to be consistent with trends observed within several published experiments of the merging process. In particular: (a) The floor flow rate onto the stairs decreases as the stair population density increases. (b) For a given stair population density, the floor population's flow rate onto the stairs can be maximized by connecting the floor to the landing adjacent to the incoming stair. (c) In situations where the floor is connected adjacent to the incoming stair, the merging process appears to be biased in favor of the floor population. It is further conjectured that when the floor is connected opposite the incoming stair, the merging process between the stair and floor streams is almost in balance for high stair population densities, with a slight bias in favor of the floor stream at low population densities. A key practical finding of this analysis is that the speed at which a floor can be emptied onto a stair can be enhanced simply by connecting the floor to the landing at a location adjacent to the incoming stair rather than opposite the stair. Configuring the stair in this way, while reducing the floor emptying time, results in a corresponding decrease in the descent flow rate of those already on the stairs. While this is expected to have a negligible impact on the overall time to evacuate the building, the evacuation time for those higher up in the building is extended while those on the lower flows is reduced. It is thus suggested that in high-rise buildings, floors should be connected to the landing on the opposite side to the incoming stair. Information of this type will allow engineers to better design stair–floor interfaces to meet specific design objectives.

KEY WORDS: evacuation, deference behavior, evacuation simulation, high rise building, stair merging behavior.

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INTRODUCTION

IN HIGH-RISE BUILDING evacuations, the nature of merging streams at the floor–stair interface is one of the controlling factors that dictate the speed at which floors can be vacated and the speed at which the occupants already on the staircase can progress down the stairs and out of the building. It is thus an extremely important component of high-rise building evacuation. Even though much has been written concerning human behavior associated with evacuation from high-rise buildings and the behavior of people while descending stairs (see for example [1–4]), little detailed attention has been focused on the merging behavior of occupant flows on staircases. While several studies have been reported in the literature dealing with the observation of merging streams on stairs [5–8] during controlled experiments and drills, there is little detailed understanding of the factors that control and influence the merging process or systematic quantification of the merging process. This lack of knowledge makes it difficult both to develop and verify advanced computer egress models for high-rise building applications. Of even greater significance, the general architectural and building engineering community is designing pedestrian flow and evacuation systems without a detailed understanding of how the basic components perform. During building evacuation it is common to see floor streams and stair streams merging on stair landings [5–8]. However, a consistent and detailed description of the merging process over a variety of scenarios involving: incident type; building type; architectural features of landings, stairs and floor–stair interfaces; crowd densities, and crowd demeanor has not been reported.

Hukugo et al. [5] describe a series of three floor–stair merging experiments involving some 150 participants. The experiments investigated the nature of the merging process at the stair landing resulting from the interaction of two streams, a stair stream created by trial participants descending from upper floors and a floor stream. The geometry of the stair was configured so that participants from the floor entered the staircase via an open door adjacent to the incoming stair (defined relative to the descending participants). The participants were divided into two groups of approximately 85 and 65 people, with the larger group entering the stair from the floor and the smaller group descending down the stair. The three different experiments involved slightly different experimental conditions and each experiment was repeated five times with the same cohort of participants. Due to the inherent complexity of the merging process, the results from this work are not straight forward to interpret. The main findings of the work relate to the establishment of steady state flow conditions in the merging region, ignoring the start up and ending phases of the merging process. The three different experimental conditions involved (i) allowing the stair stream to establish itself first and after this has been achieved, allowing the floor stream to attempt to merge (experiment 1); (ii) allowing the floor stream to establish itself first and after this has been achieved, allowing the stair stream to attempt to merge (experiment 2); and (iii) releasing both the stair and floor streams at the same time (experiment 3). A main finding of this work was that when both streams attempt to merge on the stairs at the same time (experiment 3), the flow rate into the landing merger region during steady state conditions – measured using unit flow rates – was biased in favor of the floor stream, with on average 60% of the total flow rate into the merger region being made up from the floor stream. However, if either the floor or stair streams had established itself prior to the other stream attempting to merge (experiment 1 or 2) there would be an approximate equal sharing of the merging process (i.e., 50% bias).

Takeichi et al. [6] extended the earlier experiments of Hukugo et al. [5] to consider situations where the floor stream merges with the descending stair stream in two different locations, one adjacent to the incoming stair and one opposite the incoming stair (this type of arrangement is demonstrated in Figure 2). While their experiments only consisted of some 27 participants in total – resulting in very brief measurable periods – the results suggest that the floor flow rate onto the landing is strongly dependent on the density of people on the stairs and the location of the landing door relative to the incoming stair. They demonstrated that as the density of people on the incoming stairs increases, the flow rate from the floor onto the landing decreases. Most importantly, they demonstrate that the floor flow rate onto the landing is greater when the landing door is located adjacent to the incoming stair as opposed to opposite the incoming stair. The advantage offered by connecting the floor adjacent to the incoming stair was as high as 28%, depending on the density of the incoming stair stream. While these experiments only involved a very small number of participants and thus involved very short duration merging processes, the results suggest that the geometrical or architectural features of the floor–stair interface and the density of the stair stream are of great importance in determining the nature of the merging process.

Another interesting result generated from these trials relates to the flow rate achieved by the floor stream when the landing door is initially closed. Takeichi et al. [6] noted that the flow rate onto the landing from the floor is some 30% lower when the landing door is initially closed, thereby requiring the participants to open the door and keep the door leaf from partially obscuring the door aperture. Clearly, the landing door interfered with the floor stream, thereby reducing the effective width of door resulting in a corresponding decrease in the floor flow rate.

In [7] Pauls describes the merging behaviors at floor–stair interfaces observed from a range of uncontrolled total building evacuations from the late 1960s and early 1970s. He describes a ‘fairly consistent’ pattern of deference behavior [9] in which the stair stream defers to the floor stream. Unfortunately, Pauls does not report numerical values for the actual merging flows at the floor–stair interface. However, Pauls does provide an example of hypothetical merging behavior at a floor–stair interface during an uncontrolled total building evacuation of a 15-storey building over a 15 s period in which he assumes five people from the stair stream merge with 10 people from the floor stream. This particular encounter is weighted by a factor of two to one in favor of the floor stream. In this example Pauls notes that the speed of the stair stream at floors above the interface is slowed as a result of the merging. Pauls further suggests that as the load on the stairs increases, the merging behavior will lead to complete flow stagnation on the stairs, of increasing duration for those on higher floors [7].

The type of stop–start behavior described by Pauls [7] has also been reported in observations of heavily congested stairs during evacuation drills [4,8]. Kagawa et al. [8] conducted a pre-announced evacuation drill in Tokyo of a 53-storey high-rise office building, which on the day involved some 1500 occupants. The stairs were arranged so that the floor was connected to the landing adjacent to the incoming stair. In a participant questionnaire 30% of those questioned reported slowing down or stopping while on the stairs. Furthermore, video cameras placed within the stairwell on several floors recorded complete stagnation of the stair flow which lasted for periods of 10 to 15 s [8]. In one such stagnation event on the 25th floor, Kagawa et al. describes a situation where the stair stream defers to the incoming floor stream, allowing the floor stream to enter the staircase thereby bringing the stair stream to a complete stand still for a ‘short period’ [8]. In describing the evacuation drill, Kagawa et al. state, ‘. . . this evacuation was an exercise notified in advance, and practically no psychological stress was felt by the evacuees.’ [8].

The work of Hukugo et al. [5] and Takeichi et al. [6], and others [4,7,8] suggest that the merging behavior at floor–stair interfaces is strongly influenced by physical attributes related to the architecture of the geometry and the density of the crowds on the stairs. However, these findings are based on staged experiments and evacuation drills. Under these circumstances, potentially important psychological aspects of the merging process are unlikely to emerge and exert an influence.

A simplistic assumption which may be employed in evacuation simulation software [10,11] assumes that the floor and stair streams at the floor–stair interface behave in a hydraulic manner similar to the flows of fluids in pipes. Using this analogy, the incoming floor stream and the established stair stream are regulated at the merger point according to the amount of flow from each source and the capacity of the stair. However, this type of model does not reflect one of the main experimental observations that the stair stream tends to defer to the floor stream – at least under controlled experimental conditions. On the whole, little has been reported on how computer evacuation models represent merging flows at the floor–stair interface. In a recent article describing an application of the buildingEXODUS evacuation model to an analysis of the World Trade Center evacuation of 2001 [12], Galea et al. describe in detail the congestion that develops on the stairs and on the floors during the evacuation simulation. The authors define a parameter, the Average Floor Evacuation Efficiency (AFEE) which measures for each floor the average amount of time lost by the floor occupants to congestion as a fraction of their average evacuation time. The analysis shows that the average evacuation efficiency decreases with height and as the population within the building increases, there is a corresponding greater loss of efficiency with height. This appears to be consistent with some of the comments of Pauls in [7].

Clearly it is important that the merging process is adequately represented in evacuation software. In extreme cases, if the merging nature of the flows is not correctly represented, this could lead to unrealistic situations in which the floor population gives way entirely to the stair stream or the stair stream entirely gives way to the floor stream. While this type of crude assumption is usually employed in hand calculations of evacuation used in simplistic engineering analysis [4], computer based egress models are expected to incorporate a more realistic representation of the merger process in which possession of the floor–stair interface is shared in some manner between the competing floor and stair streams.

In this article the nature of the merging process at the floor–stair interface is examined and trends found in experimental data are compared with predictions. Predictions are made using a comprehensive evacuation model that is implemented in a suite of software tools called buildingEXODUS. This software suite is designed to simulate circulation and evacuation of large numbers of people from the built environment.

EVACUATION MODELING SOFTWARE

The basis of the comprehensive evacuation model used here has been described in several other publications [12–14] and so will only be briefly noted here. The model takes into consideration people–people, people–structure, and people–fire interactions and tracks the trajectory of each individual as they move around the geometry. In evacuation applications involving fire, the model can also predict when occupants will be affected by fire hazards such as heat, smoke, and toxic gases. The software has been written in C++ using Object Orientated techniques utilizing rule base technology to control the simulation. Thus, the behavior and movement of each individual is determined by a set of heuristics or rules. For additional flexibility these rules have been categorized into five interacting sub-models, the OCCUPANT, MOVEMENT, BEHAVIOR, TOXICITY, and HAZARD sub-models. These sub-models operate on a region of space defined by the GEOMETRY of the enclosure.

Within the software, the building layout can be specified using a DXF file produced by a CAD package. The Occupant sub-model allows the nature of the occupant population to be specified. The population can consist of a range of people with different movement abilities, reflecting age, gender and physical disabilities as well as different levels of knowledge of the enclosure's layout, response times etc. The model also assigns several psychological parameters known as drive and patience to individuals that are used by the Behavior sub-model to resolve conflicts and queuing behaviors. On the basis of an individual's personal attributes, the Behavior Sub-model determines the occupant's response to the current situation, and passes its decision on to the Movement Sub-model. The Behavior model considers such behaviors as; determining the occupant's initial response, conflict resolution, overtaking, etc.

The analysis in this article is concerned with the manner in which the model resolves conflicts for space between individuals. The model uses a fine network of nodes to describe the enclosure. Each node is intended to represent the smallest amount of free space available for occupancy, essentially it is the space that a single individual can occupy. Thus only one occupant can occupy a node at a time. However, the situation often arises where two or more occupants may wish to occupy a particular node. At the first level of conflict resolution the travel time for each conflicting occupant to arrive at the node in question is examined. If the occupants are determined to arrive at the contested node during the same tick of the simulation clock they are deemed to be *in conflict*. The resolution of such a conflict is then attempted through an evaluation of the 'drive' attribute for each of the competing occupants. Here, the 'drive' is intended to be a psychological/sociological attribute representing an individual's motivation to win possession of region of space or node. The drive for each occupant involved in the conflict is compared. If one of the occupants has a drive significantly higher than the others, this occupant becomes the winner. However, if the drives are sufficiently close, the winner is randomly selected. Sufficiently close is here defined as the absolute normalized difference between the various drives being <10%.

All occupants involved in conflicts attract a time penalty that is randomly selected between pre-determined limits. The time penalty represents the time lost in the interaction. There are two levels of time penalty. The first level is associated with conflicts that are resolved on clear differences in drive. If the conflict is resolved in a random manner, the second level time penalty (which is longer than the first level) is used. Conflict losers may continue to wait in the same location until another opportunity to occupy the node arises, or perform another action such as change direction.

In addition a number of localized decision-making processes are available to each individual according to the conditions in which they find themselves and the information available to them. This includes the ability to customize their travel path according to the levels of congestion around them, the environmental conditions, the social relationships within the population and interaction with signage. As certain behavior rules, such as conflict resolution, are probabilistic in nature, the model will not produce identical results if a simulation is repeated. Individuals can also be tasked with a range of different itineraries enabling them to undertake specific functions or visit specific sites within the geometry.

DESCRIPTION OF THE NUMERICAL TEST CASES

Two numerical test cases are studied to examine the nature of the merging behavior produced by the software. Trends in numerical predictions produced by the second numerical test case are compared with trends from evacuation experiments and observations from evacuation drills [5–7].

Numerical Test Case 1: Conflict between Two Competing Streams

Numerical test case 1 involves a simple junction between two streams of flow which then continues in a single stream onto an exit (Figure 1). Competition develops between the two streams for possession of the junction region. This test case is intended to investigate the implications of the simple conflict resolution rules implemented in the software.

In this case two corridors of equal width and length labeled South and East merge in a common intersection region. From the merger region another corridor continues and ends in an exit (Figure 1). Each corridor is the same width and is capable of allowing individuals to walk down the corridor in single file. The merger region is only capable of allowing a single person to occupy the space at one time. At the end of each corridor is a source node which generates people at a given rate which effectively keeps both the South and East corridors filled and supplied with people for the duration of the simulation.

Several numerical test cases are examined. In each numerical test case, each member of the population is randomly assigned a maximum travel

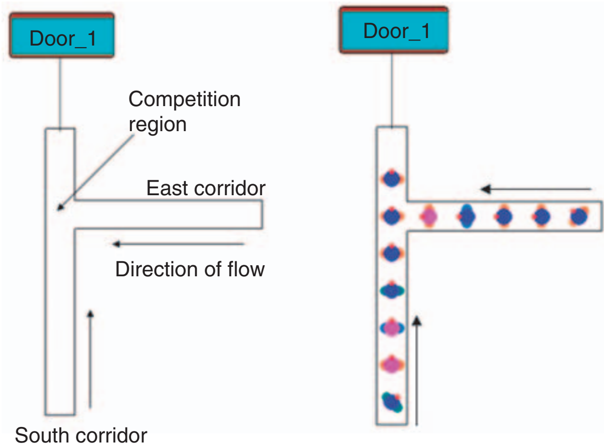

__Figure 1.__ Geometry for case 1 scenario showing competition region created from two competing population streams.

speed of between 1.0 m/s and 1.5 m/s. In numerical test case 1a, population POP1 is used, in which each member of the population is assigned an identical drive value, in numerical test case 1b population POP2 is used in which each member of the population is randomly assigned a drive between a given range and in numerical test case 1c, one stream is made up of population POP2 while the other is made up of population POP3 (Table 1).

Numerical Test Case 2: Interaction at the Floor–Stair Interface

Numerical test case 2 is more representative of a floor–stair interface and represents a landing with dogleg stairs. One set of stairs approaches the merging landing from the floor above while another set of stairs continues from the merging landing to the landing below. Two different configurations are examined: In Test Case 2a, the door from the floor is adjacent to the incoming stair while in Test Case 2b, the door from the floor is on the opposite side of the landing to the incoming stair (see Figure 2 and Figure 3(a) and 3(b), respectively). This test case is used to examine more complex behavior associated with merging flows at the floor–stair interface.

The landing has dimensions of 1.5 m wide by 3.0 m long and the incoming/outgoing stair has a width of 1.5 m with 9 risers. The door leading onto the landing is 1 m wide and can allow two people through at a time. In each case, the door is located in the corner furthest from the stairs and on the wall perpendicular to the stairs (Figure 2). The door is assumed to be fully open at the start of and during the simulation and does not obstruct either the stair or the floor population. Within the software, the landing can accommodate

Table 1. Relevant population parameters for numerical test case 1.

Population	Test case	Range of travel speeds	Range of drives
POP1	1a	1.0 m/s–1.5 m/s	Identical drives
POP2	1b and 1c	1.0 m/s–1.5 m/s	1.0 to 10.0
POP3	1c	1.0 m/s–1.5 m/s	1.0 to 5.0

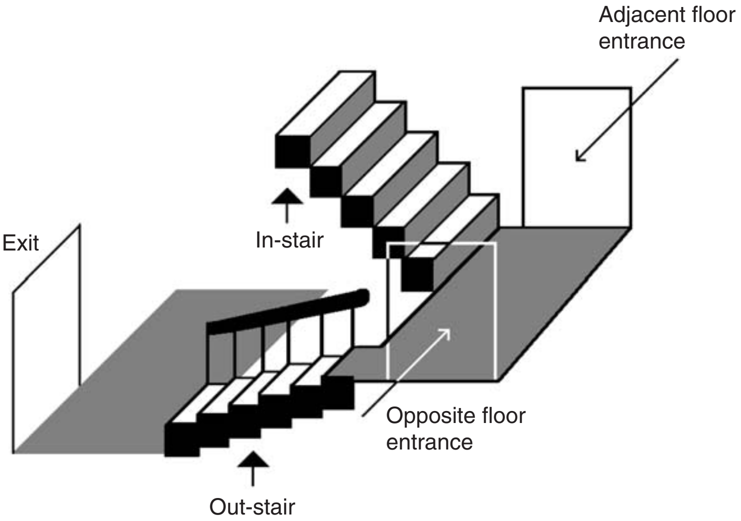

Figure 2. *Geometry for numerical test case 2 showing two alternative floor–stair interface regions on main landing.*

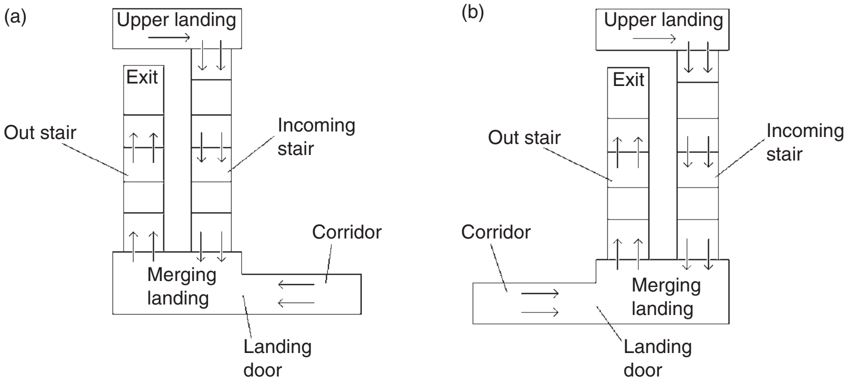

Figure 3. *Representation within the software of the two geometries investigated in numerical test case 2 with the floor connected to the landing adjacent to (a) and opposite to (b) the incoming stair.*

a maximum of 18 modeled individuals (producing a population density of 4 p/m^2), while the stairs can accommodate a maximum of two people per tread. A corridor was connected to the landing via the door. The corridor was some 4.5 m long and sufficiently wide to allow two people abreast (Figure 3).

The floor population was generated using source nodes, as in numerical Test Case 1, placed at the end of the corridor. The stair population was generated using sources nodes placed on the upper landing of the incoming stair. The populations used in this numerical test case consisted of a random mixture of people with drives varying from 1 to 10, the default range of stair speeds, ranging from 0.60 m/s to 1.01 m/s (measured along the slope) and speeds on flat terrain varying from 1.0 m/s to 1.5 m/s. The same mixture of people was used to define the floor and stair populations. The floor population was generated so as to maintain an average population density of 4 people/m^2 in the corridor. This meant that there was always a ready supply of floor people attempting to enter the stair.

Two different population densities were used on the stairs, a high and a low population density. These were set by adjusting the generation rate of the source node located on the upper landing. The generation rate was adjusted so that in the case with the floor connected to the landing opposite the incoming, an average population density of 2.5 p/m^2 would be maintained on the incoming stair for the high density case and an average population density of 1.5 p/m^2 would be maintained for the low density case. In total, four different numerical test cases were performed using the two stair geometries and the two populations.

RESULTS

Numerical Test Case 1: Conflict between Two Competing Streams

Each simulation was run for a simulated time of 1 h producing some 2400 people in total. Each 1 h simulation was repeated 10 times and the average results for a 1 h period are presented.

Numerical Test Case 1: Equal Drives

As the simulation commences and both the south and east approach corridors are fully occupied, the first person from each stream comes into conflict to occupy and pass over the intersection region. As each person arrives at the conflict point at about the same time and as their travel speeds are very similar, they will each be able to occupy the conflicted space at the same time. Thus possession of the space is determined by the drives of the conflicting individuals. As each person in each stream has identical drives the resolution of each conflict is determined randomly. With the resolution of each conflict, the winning individual occupies the space and then moves onto the exit corridor to exit the simulation. As the conflicted space is released, the next pair of individuals now compete for the space which is then resolved in a similar manner.

The number of people occupying the conflict region determined over 10 min periods, averaged over the 10 simulations is presented in Figure 4. Over the entire period a total of 1107 individuals from the east stream won possession of the conflict region while some 1087 individuals from the south stream won possession. Thus it can be seen that overall there is an almost even split in possession of the conflict region. As possession of the region is determined randomly this is to be expected. If each 10 min period is examined, it is found that possession of the conflict region is evenly distributed between both streams (within 10%).

If the interactions are examined in detail, it is found that in any given set of encounters, one stream may typically win from one to four encounters in a row, while occasionally winning up to 10 or 14 encounters in a row. The norm appears to involve possession of the conflict region frequently alternating between both streams, allowing only short bursts of people from one stream to pass through. In any 1 h period, possession of the conflict region on average changes hands 1000 times.

Numerical Test Case 1b: Range of Drives

As in the previous case, possession of the conflict region is determined by comparison of the drives of the conflicting individuals. However, in this case

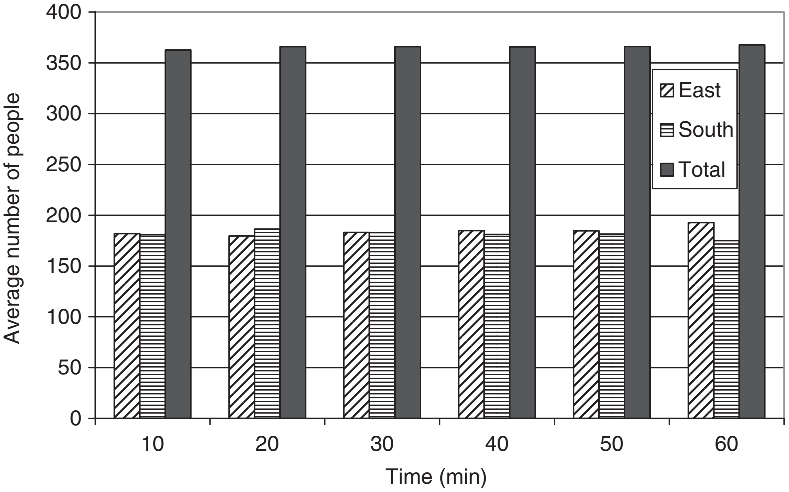

Figure 4. *Average occupancy of the conflict region in numerical test case 1a (same drives).*

each individual potentially has a different drive randomly generated from a distribution of 1 to 10. Also, each stream has an identical range of drives so while the drives of each person may vary, one stream does not have more 'driven' people than the other.

As each persons drive is potentially different, the resolution of each conflict is determined first by comparison of the values of the drive to determine which person has the larger drive. If the drives of the competing individuals are within 10% of each other, then the outcome of the conflict is determined randomly. If not, then the conflict is resolved in favor of the individual with the larger drive.

The number of people occupying the conflict region determined over 10 min periods, averaged over the 10 simulations is presented in Figure 5. Over the entire period a total of 1199 individuals from the east stream won possession of the conflict region while some 1199 individuals from the south stream won possession. Thus it can be seen that overall there is an even split in possession of the conflict region. As the drive distribution for each stream is identical, this result may be expected. While taken over the entire 1 h period, the possession of the conflict region is evenly distributed between both streams. However, when each 10 min period is examined, a different picture emerges. In the latter case, there are two periods in which possession of the conflict region is evenly distributed between both streams (within 10%) and four periods where one stream dominates over the other

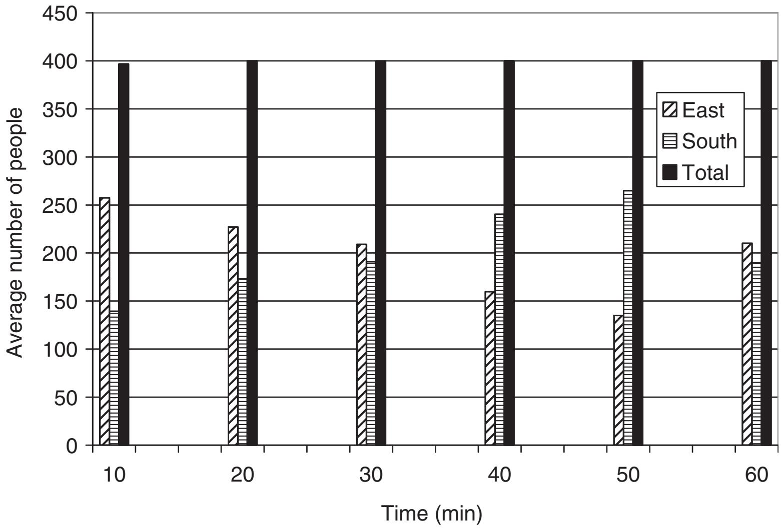

Figure 5. *Average occupancy of the conflict region in numerical test case 1b (drive range from 1–10).*

by more than $\sim 30\%$. In two periods, the east stream has a 30% and an 85% advantage over the south stream and in two periods the south stream has a 50% and 96% advantage over the east stream.

If the interactions are examined in detail, a very different pattern emerges from that observed in numerical Test Case 1a where all the competing individuals had identical drives. Here it is found that it is normal to have very long periods in which one stream dominates over the other with very few situations in which one stream wins only a few (e.g., one to four) encounters in a row. Situations in which one stream may win 30 encounters in a row are common. In contrast to the previous case, the norm in numerical test case 1b appears to involve possession of the conflict region infrequently alternating between both streams, allowing long bursts of people from one stream to pass through. In any 1 h period, possession of the conflict region may change hands only 25 times, a factor of 40 times less frequently than in numerical Test Case 1a.

Numerical Test Case 1c: Different Range of Drives in Each Stream

In this numerical test case, the drive in the south stream is randomly distributed from 1 to 5 while in the east stream the drive is randomly distributed from 1 to 10. Thus the people in the east stream are more 'driven' than those in the south stream. As 50% of the individuals in the east steam are likely to have drives higher than the maximum drive in the south stream, it would be expected that the east stream wins the majority of conflicts in which the conflict is resolved by magnitude of the drive.

The number of people occupying the conflict region determined over 10 min periods, averaged over the 10 simulations is presented in Figure 6. Over the entire period a total of 1778 individuals from the east stream won possession of the conflict region while some 618 individuals from the south stream won possession. Thus it can be seen that overall there is a bias of 2.9 to 1.0 in favor of the east stream. As individuals in the east stream have significantly higher drives this result is to be expected. If each 10 min period is examined, it is found that there are three periods in which the possession of the conflict region is won by the east stream in a ratio exceeding 3.0 to 1.0 and three occasions in which the east stream wins the conflicts in a ratio between 2.2 to 1.0 and 2.6 to 1.0.

Clearly, by specifying the range of drives of the population in the competing streams, possession of the conflict region can be biased in favor of one stream over the other, both over the long term and over shorter duration periods.

If the interactions are examined in detail, it is found that there is a similar pattern emerging to that observed in numerical test case 1b where both streams had identical drive distributions. Once again, the norm is to have long

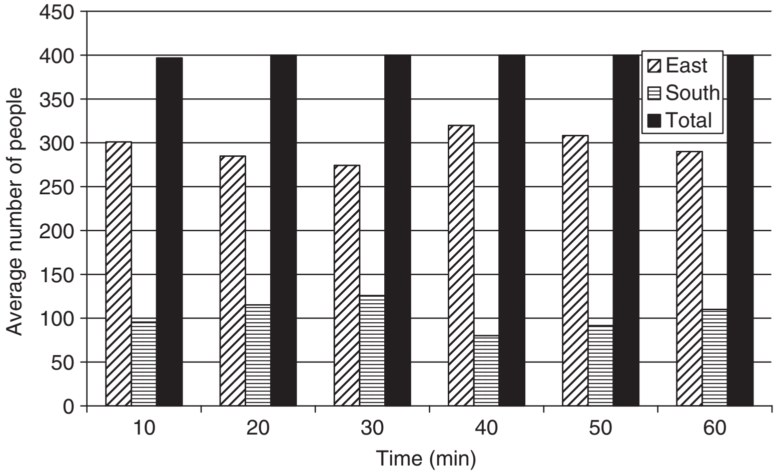

Figure 6. *Average occupancy of the conflict region in numerical test case 1c (drive range east 1–10, south 1–5).*

periods in which one stream dominates over the other with few situations in which one stream wins only a few (e.g., one to four) encounters in a row. However, in any 1 h period, possession of the conflict region may change hands 35 times on average, a factor of 30 times less frequently than in numerical test case 1a and almost twice as frequently as in numerical test case 1b.

Discussion of Numerical Test Case Results

Within the evacuation simulation software, in situations where there is a direct competition for limited space between two competing streams of occupants, possession of the space is determined by the drive parameter. If the drive's of each occupant within each stream are identical, the conflicts are determined purely randomly and over a sufficiently long period of time each stream will win possession of the conflict region an equal number of times. Over short periods of time, one stream may win possession of the conflict region for very short durations allowing two to four people from the winning stream to pass. The situation then flips and the opposing stream may win possession for a brief period.

If the drives within each stream are randomly distributed between equal limits, then once again, over the long term each stream will win possession of the conflict region an equal number of times. However, when viewed over shorter durations, one stream may win possession of the conflict region for a relatively long duration allowing up to 30 people from the winning stream to pass. By biasing the drive distributions so that one stream has more individuals with higher drives, it is possible to allow one stream to win out over the other, both in the long term and in the short term. Short term advantages of 2.2 to 1.0 up to 4.0 to 1.0 can be achieved by allowing 50% of the individuals in one stream to have a drive of up to 50% higher than the largest drive of the other stream. This is a useful and realistic feature as it allows the conflict resolution within the simulation model to be variable (rather than fixed throughout a simulation) based on the assigned parameters of the interacting individuals.

The conflict situation arising at the floor–stair interface is more complex than the situation just described. This is due in part to there being more space available on the landing resulting in a situation in which individuals from the floor and stair may not in fact be in direct competition. However, the type of behavior described above fits the general observations of merging behavior at the floor–stair interface, in particular, the sharing of access between the competing streams and on occasion under certain conditions, one stream may dominate the interface by factors of 2.0 to 1.0 or greater.

Numerical Test Case 2: Interaction at the Floor–Stair Interface

Each simulation in numerical Test Case 2 was run for a simulated time of 10 h in which approximately 35,000 people on average were generated and passed through the floor–stair interface region. Long run times involving many people were used so as to produce statistically meaningful results. In each case the generation rate on the source nodes were set so as to produce a constant supply of people feeding both the stair stream and the floor stream. Thus both the stair and floor streams had access to sufficient people to ensure that their flow would not stop due to lack of supply of people during the simulation period.

Presented in Table 2 is a summary of the predicted flow rates into the merger region from the floor and incoming stair for the four numerical test cases. It is noted that within each pair of cases (i.e., the first pair of cases, cases 2a and 2b and the second pair of cases, cases 2c and 2d) the average density on the incoming stair varies considerably, making meaningful comparisons difficult. For numerical test cases 2a and 2b the average population density on the incoming stair varies from 2.5 p/m^2 to 4.0 p/m^2, respectively. This variation can be explained as follows.

The population density on the incoming stair is controlled by two mechanisms, the people generation rate (or supply) and the flow rate down the stair (or demand). A constant supply rate of people (33 p/min) was initially selected so as to provide an average population density of 2.5 p/m^2 in numerical test case 2a. Keeping the generation rate constant at 33 p/min for cases 2a and 2b ensures that in each case the incoming stair has access to, and must attempt to process the same number of people. This allows for a

Table 2. Predicted flow rates in the merger region for two landing door locations and various average stair population densities.

Numerical test case	Stair population generation rate (p/min)	Incoming stair average population density (p/m^2)	Floor stream flow rate through landing door (p/(m s))	Stair stream flow rate onto landing (p/(m s))	Flow rate down out-stair (p/(m s))
2a: Landing door opposite incoming stair	33.0	2.5	0.48	0.51	0.99
2b: Landing door adjacent incoming stair	33.0	4.0	0.75	0.24	0.99
2c: Landing door opposite incoming stair	27.0	1.4	0.56	0.43	0.99
2d: Landing door adjacent incoming stair	27.0	4.0	0.74	0.25	0.99
2e: Landing door adjacent incoming stair	14.0	2.8	0.76	0.23	0.99
2f: Landing door adjacent incoming stair	3.0	1.4	0.95	0.05	0.99

fair comparison to be made between both these cases. The second factor controlling the stair population density is the flow rate down the stair (or the demand) which is controlled by the nature of the interaction taking place in the merger region. As the flow rate down the stair (or demand) in case 2b (0.24 p/m.s) is smaller than that of case 2a (0.51 p/m.s), while at the same time the supply of people is kept constant (33 p/min), higher stair densities are generated in case 2b. For cases 2c and 2d a smaller generation rate (or supply) of 27 p/min was initially used to produce smaller average densities (1.4 p/m^2) in case 2c. A similar phenomenon to that described above creates a higher average density on the incoming stairs in test case 2d (4.0 p/m^2) compared to test case 2c (1.4 p/m^2).

As the density in case 2a differs from that of 2b and the density in case 2c differs from that of 2d it is difficult to make meaningful comparisons between these cases. As a result it is necessary to run two additional cases to ensure that for a given incoming stair density, there are results for the two stair configurations. Thus the cases with the floor connected adjacent to the incoming stairs were run again with smaller population generation rates. This produced two additional cases, case 2e generating an average incoming stair population density of 2.8 p/m^2 (with a generation rate of 14 p/min) and case 2f generating an average incoming stair population density of 1.4 p/m^2 (with a generation rate of 3.0 p/min). In these additional cases, the stair effectively caters to fewer people. For the purposes of the remaining discussion in this article, the population densities in cases 2a/2e and 2c/2f set the high density and low density regimes, respectively. Comparison among these four cases will be the focus of the discussion that follows.

The flow rate down the out-stair in each case is approximately identical and equal to 0.99 p/(m s). This indicates that the out-stair is working to maximum capacity in each case with the floor and incoming stair streams being regulated in each case by the process taking place in the merger region and the maximum capacity of the out-stair. When one of the incoming streams experiences a decrease, the other will increase to take up the slack, there being sufficient people feeding each stream. It is worth noting that in each of the cases examined, the densities on the landing were high, being on average no less than 2.6 p/m^2.

The data presented in Table 2 reveal several important trends each of which are examined in turn. The first observation concerns the impact of the incoming stair population density on floor flow rate. Regardless of whether the landing door is connected opposite or adjacent to the incoming stair, as the population density on the incoming stairs increases, the flow rate from the floor onto the landing decreases. This can be seen by comparing case 2c with 2a (opposite location) and case 2f with 2e (adjacent location). This observation is consistent with the experimental trends found in [6].

The second observation concerns the location of the landing door and its impact on flow rate. Regardless of the population density on the incoming stair, a landing door located adjacent to the incoming stair will favor the floor flow, producing higher floor flow rates compared with situations where the door is located opposite the incoming stair. This observation is also consistent with the experimental trends found in [6]. This result can be generated by either ensuring that the supply of people on the stair is fixed or keeping the incoming stair density fixed while the floor connection is changed from adjacent to opposite the incoming stair. In the numerical test cases, the floor flow rate onto the landing increased by 58% when the location of the landing door is changed from opposite to adjacent in the high stair density case (i.e., comparing cases 2a and 2e) and 70% in the low stair density case (i.e. comparing cases 2c and 2f). In [6], the actual advantage provided by placing the floor connection adjacent to the incoming stair was 28%.

The advantage provided by connecting the floor adjacent to the incoming stair observed in both the physical experiments [6] and the numerical test cases can be explained by the nature of the interaction between the two competing streams. When the door is located in the adjacent location (Figures 2 and 3), the floor and incoming stair streams merge in such a way as the two streams are essentially traveling in the same direction. The incoming stair stream turns away from the floor stream resulting in a relatively easy merger with few conflicts for space. When the door is located in the opposite location (Figures 2 and 3), the floor and incoming stair streams essentially meet head on. Thus there is a greater degree of conflict for space in this case then in the case with the adjacent door. Within the software, these conflicts are resolved using the Drive attribute as described in the previous numerical test case (Test Case 1). As these conflicts take place virtually opposite the landing door they further restrict floor flow onto the landing, especially in the case with the higher densities on the incoming stairs. As a result, the flow rate from the floor diminishes.

The third observation concerns the nature of the deference behavior in the stair–floor merger region. Data from evacuation experiments and drills suggests that the stair stream defers to the floor stream [5–8]. In [7] it was suggested that 67% of the total flow into the stair–floor merger region may be made up from the floor stream. However this suggestion, while based on the experience gained from observing many evacuation drills, was not based on actual measurements and furthermore, the stair/landing configuration was not reported. From [5] it was noted that when the landing door is connected adjacent to the incoming stair, the flow into the landing merger region during steady state conditions was biased in favor of the floor stream, with 60% of the total flow rate into the merger region being made up from the floor stream. The conditions in numerical Test Case 2e (incoming stair adjacent to the floor flow) are considered to most closely match those found in [5]. For this numerical test case, it is found that the floor stream into the merger region makes up 76% of the total flow rate. This value, while larger than the value found in the physical experiment, is consistent with general observations found in the physical experiment. In the low density numerical test case (case 2f), the floor stream into the merger region is again dominant over the stair stream and makes up 95% of the total flow. This large dominance of the floor stream over the stair stream is due to the extremely small stair population generation rate (3.0 p/min) required to produce the low population density and thus should not necessarily be considered representative.

Unfortunately, there are no published experimental data that describe the nature of the merging process when the floor is connected opposite the incoming stair. The numerical predictions for this case are dependent on the population density on the incoming stair. For high incoming stair population density (case 2a) it is noted that the flow into the stair–floor merger region is equally balanced, with the floor stream contributing 49% and the stair stream contributing 51%. This suggests a 'one for one' mixing in the merger region. For the low density case (case 2c) the floor stream appears to slightly dominate the merging process with 57% of the flow rate into the stair–flow merger region being contributed by the floor stream.

While various observations of physical experiments suggest that the floor stream has the advantage over the incoming stair stream, the nature of the stair geometry is not always noted (e.g., in [7]), or not all the relevant flow rates are mentioned (e.g., in [6,8]) or the scenario in which the floor is connected to the landing opposite the incoming stair has not been investigated (e.g., in [5]). Thus it is difficult to determine whether the predicted situations in which the stair flow and floor flow are almost balanced (i.e., numerical test case 2a and 2c) are an aberration or a real result.

As noted earlier, the situation with the landing door located opposite the incoming stair, results in a large number of potential space conflicts as the floor stream and the stair stream interact. The number of conflicts increases as the incoming stair density increases (i.e., case 2a). Most of these conflicts will be resolved using the drive attribute. As noted in numerical Test Case 1b, given that both streams have the same drive distribution, over the long run, these conflicts will be resolved equally between the two competing streams, hence the almost equivalent flow rates into the merger region observed in numerical test case 2a.

If it is assumed that the stair stream will *always* defer to the floor stream then by adjusting the drive attribute of the floor and/or stair streams the conflicts can be resolved in favor of the floor stream as described in numerical Test Case 1c. By maintaining the drive distribution of the floor steam (1 to 10) and decreasing the drive of the stair stream (from 1 to 10 to 1 to 5), the majority of space conflicts will be resolved in favor of the floor stream. When this is implemented, it is found that the floor flow rate is increased by 4% and represents some 53% of the flow rate into the merger region. Thus, while still essentially balanced, it is noted that the floor stream has a slight advantage over the stair stream. Such behavior, if it can be shown to be a real phenomenon could be represented within the current model through the introduction of a variable drive concept. This concept is further discussed in the next section.

DISCUSSION

Unlike the example of the simple merging streams described under the results for numerical Test Case 1, which were resolved by the drive parameter alone, the nature of the merging streams on staircases is considerably more complex. In addition to the conflict resolution methodology provided by the drive parameter, the configuration of the merger region must also be considered. Model predictions suggest that the representation of the floor–stair merging process within the software appears to be consistent with trends observed within several contrived experiments [5,6] and expert opinion based on experience of observations of previous evacuation drills [7]. In particular:

- The floor flow rate onto the stairs decreases as the average stair population density increases [6,7].
- The floor flow rate onto the stairs can be maximized by connecting the floor to the stair landing so that the floor population emerges onto the landing adjacent to the incoming stair [6].
- In situations where the floor is connected adjacent to the incoming stair, the merging process appears to be biased in favor of the floor population [5,7] i.e., the stair stream defers to the floor flow.

A model prediction which is neither supported nor contradicted by experimental data is that when the floor is connected opposite the incoming stair, the merging process between the stair and floor streams appears to be almost in balance for high average stair population densities, with a slight bias in favor of the floor stream at low average stair population densities. Experimental data is required to verify this observation.

These results suggest that considerable advantage in the speed at which a floor can be emptied can be derived simply by connecting the floor to the side adjacent to the incoming stair. Connecting the floor to the staircase in this manner eases the process by which the floor population can merge with the descending stair stream as both streams are traveling in essentially the same direction. However, if the floor is connected to the landing on the opposite side of the incoming stair, then floor and stair streams can collide within the merging region, creating conflicts for space and increasing the overall time required to vacate the floor. Numerical predictions suggest that in high stair density situations, the improvement in floor emptying times (achieved by connecting the floor adjacent to the incoming stair) can be as much as 58%. However, the improvement in floor emptying time has a negative impact on the stair flow rate, with the flow rate of those descending from higher floors decreased by some 55%. Thus overall, there is expected to be negligible impact on the overall time to evacuate the building. However, the evacuation time for those lower down in the building is expected to be reduced at the expense of those higher up in the building. This is precisely opposite to what should be achieved during high-rise building evacuations. Apart from those occupants on the fire-incident floor(s), it would generally be better if the floor flows did not unnecessarily impede the flow of occupants already on the stairs. This is so those descending from high in the building, and hence with the greatest egress time, are not further penalized by delays resulting from the merging of occupants on lower floors. It is thus suggested that in high-rise buildings, floors should be connected to the landing on the opposite side to the incoming stair.

Based on a combination of observations of physical experiments, numerical simulations and theoretical considerations, it appears reasonable to suggest that the merging behaviour occurring at the floor-stair interface is controlled by a complex combination of physical and social factors. The physical factors are made up of the architectural features of the environment and the physical attributes of the merging streams. The architectural features that appear to exert an influence are; the location of the door leading onto the landing, the width of the door, the positioning of the door leaf relative to the merging streams, area of the merging region, dimensions of the landing, etc. The physical attributes of the merging streams that are likely to exert an influence relate to the population density in each stream and in the merging region, the travel speed of the individuals at the merger interface and in some situations, the physical strength of the individuals competing to gain entry to or proceed through the floor-stair interface.

The social factors relate to the psychological and sociological aspects that influence the behaviour of the individuals within the merging streams. The psychological aspects that are likely to exert an influence are the motivation (or, using the terminology of the evacuation model, drive) of the individuals at the floor-stair interface which is expected to be strongly influenced by the sense of urgency felt by the competing individuals as a result of the evacuation process. This in turn may be related to the sense of personal risk perceived by the individuals in the competing floor and stair streams. The sociological aspects that are likely to exert an influence are those that determine the etiquette of normal crowd interaction and deference behaviour including: preferred inter-person spacing; gender considerations (e.g. males allowing females to pass); age considerations (e.g. younger participants allowing elderly participants to pass) and inter-personal considerations (e.g. staff-client/patron interactions). Thus some of the sociological factors will be influenced by the nature of the building occupancy (e.g. office building, residential, hospital, etc). Furthermore, many of the sociological factors may have a cultural component, differing from one society to another.

An example of normal deference behavior is frequently observed when passengers disembark a crowded aircraft just after landing. In this case, the competing streams of people consist of those passengers already in the aisle and the passengers in the seat rows attempting to gain access to the aisle. The passengers in the aisle stream often defer to the passengers in the seat rows, allowing them to gain access to and merge with the aisle stream. As a result, the aircraft usually empties from the front to the rear. However, if passengers in the aisle are highly motivated, by for example perceived time constraints, they are less likely to defer to passengers in the seat rows. Indeed, studies of passenger behavior in actual aircraft emergency situations reveal that aisles can become heavily congested, with passengers in the seat rows forced to climb over seats as they cannot easily gain access to the aisles [15].

In the current implementation of the egress model some of these sociological aspects may be crudely represented by the drive attribute and conflict resolution mechanism. By providing both competing populations with a range of drives a complex pattern of deference behavior can be generated within the interaction region. As shown in the first set of numerical test cases, if the drive distribution in each stream is equal, while on average there will be an equal sharing of the conflict region, in any one period, one stream may appear to have the advantage. By combining the drive/conflict resolution model with the inherent physical aspects of stair–floor environment, the software used in this study appears to reasonably capture the gross interactive behavior observed on stairs in the reported controlled experiments.

To a certain extent the social influences are contextual and are governed by the nature of the triggering incident. Thus the merging behavior observed in a fire drill, a staged experiment, a false alarm, a real incident in which there is no sense of danger and a real incident in which there is a real and immediate sense of danger (at least for some of the participants), may lead to very different merging behaviors, even though the physical factors in all these incidents may be identical. Indeed, the nature of the merging behavior may change as the level of perceived immediate threat increases or decreases. Thus staged evacuation experiments and evacuation drills, such as those of [4–8], can generally only hope to provide a partial understanding of the merging process, limited primarily to those situations in which the personal risk perceived by individuals is relatively low and hence the physical and sociological factors dominate. It is suggested that in a situation where the population perceives a high level of personal risk, psychological factors such as motivation (or drive) may dominate over sociological factors such as the normal deference behavior. In these circumstances, the nature of the merging behavior may be very different to that observed in trials and predicted by models.

Based on the limited data currently available from physical experiments and evacuation drills, the software used in this study appears to be able to reasonably represent the physical and some of the social factors that influence the floor-stair merging process observed in these situations. However, as already suggested, in real emergency situations as the level of risk perceived by individual's increases, the associated motivation to leave the structure may also increase. Furthermore, heightened levels of perceived risk may be non-uniformly distributed throughout the building depending on for example, an individual's position relative to, or knowledge and understanding of, the developing hazard or threat. If such behaviour can be shown to be both realistic and to exert a significant influence on merging behaviours they will need to be represented within evacuation software.

It was demonstrated in this study that by increasing the drive distribution of one stream relative to the other, the stream with the elevated drives could be made more likely to win the conflicts and hence dominate possession of the floor-stair merger region. To represent this type of behaviour within the evacuation software used in this study, it may be necessary to introduce a dynamic drive parameter, where an individual's drive varies depending on for example, their emotional state or level of perceived risk. As the level of personal risk perceived by the individual increases or decreases, so would their drive. Using such a device, an individual's propensity to win space conflicts will increase as their drive increases. The behaviour model could also be extended so that above a critical drive level, individuals may not be prepared to willingly defer to others.

To derive a more complete understanding of the merging process it is necessary to undertake detailed studies of evacuation trials and more importantly real emergency evacuation situations. Real emergency evacuation situations can be analysed through video footage from CCTV if it exists and face to face interviews with survivors. The former approach would be greatly enhanced if CCTV cameras were routinely fitted to the emergency stairs of high-rise buildings. For example, cameras installed on the main landing of every fifth floor [16] could provide a wealth of information on: the merging process; stair behaviour; travel speeds as a function of occupant density; the movement of the disabled and the interaction of emergency services personnel travelling in contra-flow to the descending building population. Unfortunately there appears to be a reticence to install CCTV cameras within staircases, and so the later approach is currently being pursued as part of a UK study of the World Trade Center evacuation of 9/11 [17,18]. As part of the interview procedure, the merging process experienced by survivors attempting to enter the stairs and those already on the stairs is being explored. It is hoped that this study will provide some insight into the nature of the physical and social processes occurring at the floor-stair interface in real emergency situations. This information may support the concept of dynamic drive described above, or lead to other model modifications.

Finally, modelling analysis has suggested that modifying the deference behaviour of interacting streams in merging situations may have a significant impact on the performance of both interacting streams. In essence by controlling deference behaviour the stream with the greatest need may be given priority. Thus in real high-rise building evacuation situations, if a means could be found to control the deference behaviour of interacting floor and stair streams, the evacuation dynamics could be tuned to provide maximum benefit to the sub-population most in need. Modelling could be used to quantify the likely gains that could be achieved through incremental adjustment of the merging behaviour. Unfortunately, while modifying deference behaviour in a computer model is relatively straightforward, controlling real human behaviour in this way is likely to present more significant challenges that are unlikely to be addressed by simple solutions such as training.

CONCLUDING COMMENTS

This article has investigated the merging behavior at the floor–stair interface during building evacuations. There are two sets of conclusions from this work, one referring to the manner in which the buildingEXODUS evacuation software represents merging behavior and another relating to the nature of the observed general trends of the merging behavior.

Based on the limited detailed data currently available from physical experiments and evacuation drills, the buildingEXODUS software appears to be able to reasonably represent the physical and some of the social factors that influence the floor–stair merging process observed in these situations. However, as the current detailed knowledge base is limited to contrived experiments and evacuation drills, it is not clear if the observed behaviors are sufficient to describe the merging process in real emergency situations.

A key finding of this analysis is that considerable advantage in the speed at which a floor can be emptied can be derived simply by connecting the floor to the side adjacent to the incoming stair rather than to the side opposite the stair. Connecting the floor to the staircase in this manner eases the process by which the floor population can merge with the descending stair flow as both flows are traveling in essentially the same direction. Numerical predictions suggest that in high stair population density situations, the improvement in floor emptying times can be as much as 58%. However, the improvement in floor emptying time has a negative impact on the stair flow rate, with the flow rate of those descending from higher floors decreased by some 55%.

Thus overall there is expected to be negligible impact on the overall time to evacuate the building; however the evacuation time for those higher up in the building is expected to be extended. It is, therefore, suggested that in high-rise buildings, floors should be connected to the landing on the opposite side to the incoming stair. While these findings also apply to other multi-storey buildings, the nature of the required stair–floor connectivity will be dependent on the overall evacuation strategy being implemented. However, it should again be noted that as the current detailed knowledge base is limited to contrived experiments and evacuation drills it is not clear if the observed behaviors are sufficient to describe the merging process in real emergency situations.

A model prediction which is neither supported nor contradicted by experimental data is that when the floor is connected opposite the incoming stair, the merging process between the stair and floor flows appears to be almost in balance for high average stair population densities, with a slight bias in favor of the floor flow at low average stair population densities. Experimental data are required to verify this observation.

To derive a more complete understanding of the merging process it is necessary to undertake further detailed studies of both experimental trial and real evacuation situations. The later is currently being pursued as part of a UK study of the World Trade Center evacuation of 9/11 involving face to face interviews with survivors. It is hoped that this study will provide some insight into the nature of the physical and social processes occurring at the floor-stair interface in real emergency situations and thereby provide guidance on future enhancements to evacuation models.

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REFERENCES

1. Pauls, J.L., ‘‘Movement of People in Building Evacuations’’, In: Conway, D.J., ed., Human Response to Tall Buildings, CDS/34, Hutchinson and Ross, Inc, Dowden, 1977, pp. 281–292.
2. Fruin, J.J., Pedestrain Planning and Design, Metropolitan Association of Urban Designers and Environmental Planners, Inc., New York, 1971.
3. Proulx, G., ‘‘The movement of People: The Evacuation Timing’’, In: DiNenno, P.J., Beyler, C.L., Custer, R.L.P., Walton, W.D., Watts, J.M., Drysdale, D., Hall, J.R., eds., SFPE Handbook of Fire Protection Engineering, 3rd edn, NFPA International, Quincy, MA USA, 2002, pp. 3–342 to 3–366.
4. Nelson, H.E. and Mowrer, F.W., Emergency Movement., ‘‘Emergency Movement’’, In: DiNenno, P.J., Beyler, C.L., Custer, R.L.P., Walton, W.D., Watts, J.M., Drysdale, D., Hall, J.R., eds., SFPE Handbook of Fire Protection Engineering, 3rd edn, NFPA International, Quincy, MA USA, 2002, pp. 3–367 to 3–380.
5. Hokugo, A., Kubo, K. and Murozaki, Y., ‘‘An Experimental Study on Confluence of Two Foot Traffic Flows in Staircase,’’ Journal of Architecture, Planning and Environmental Engineering, No. 358, Architectural Institute of Japan, Dec, 1985, pp. 37–43.
6. Takeichi, N., Yoshida, Y., Sano, T., Kimura, T., Watanabe, H. and Ohmiya, Y., ‘‘Characteristics of Merging Occupants in a Staircase’’, In: Gottuk, D.T. and Lattimer, B.Y. eds., Fire Safety Science, Proceedings of the Eighth International Symposium, International Association for Fire Safety Science, London, 2006, pp. 591–598.

7. Pauls, J.L., ''Suggestions on Evacuation Models and Research'', Human Behaviour in Fire, 3rd International Symposium, Interscience, London, 2004, pp. 23–33.
8. Kagawa, M., Satoshi, K. and Morishita, Y., ''Movement of People on Stairs during Fire Evacuation Drill – Japanese Experience in a High Rise Office Building'', Fire Safety Science, In: Grant, C.E. and Pagni, P.J. eds., Proceedings of the First International Symposium, Hemisphere Publishing Corp, USA, 1986, pp. 533–540.
9. Pauls, J. and Jones, B., ''Building Evacuation: Research Methods and Case Studies'', In: Canter, D. ed., Fires and Human Behaviour, Wiley, London, 1980, pp. 227–249.
10. Gwynne, S., Galea, E.R., Owen M., Lawrence P.J. and Filippidis L., ''A Review of the Methodologies Used in Evacuation Modelling'', Fire and Materials, Vol. 23, No. 6, Nov–Dec 1999, pp. 383–389.
11. Kuligowski, E.D. and Peacock, R.D., A Review of Building Evacuation Models, NIST Technical Note 1471, Gaithersburg, MD USA, 2005.
12. Galea, E.R., Sharp, G., Lawrence, P.J. and Holden, R., ''Approximating the Evacuation of the WTC North Tower Using Computer Simulation'', Journal of Fire Protection Engineering, Vol. 18, No. 2, 2008, pp. 85–115.
13. Gwynne, S., Galea, E.R., Lawrence, L. and Filippidis, L., ''Modelling Occupant Interaction with Fire Conditions Using the building EXODUS Evacuation Model'', Fire Safety Journal, Vol. 36, 2001, pp. 327–357.
14. Park, J., Gwynne, S., Galea, E.R. and Lawrence, P., ''Validating the buildingEXODUS Evacuation Model Using Data from an Unannounced Trial Evacuation,'' In: Galea, E.R. ed., Proceedings of the 2nd International Pedestrian and Evacuation Dynamics Conference, ISBN 1904521088, CMS Press, Greenwich, UK, 2003, pp. 295–306.
15. Galea, E.R., Finney, K.M., Dixon, A.J.P., Siddiqui, A. and Cooney, D.P., ''Aircraft Accident Statistics and Knowledge Database: Analyzing Passenger Behavior in Aviation Accidents,'' AIAA Journal of Aircraft, Vol. 43, No. 5, 2006, pp. 1272–1281.
16. Pauls, J., Private communication 30 May 2007.
17. Project HEED, www.wtc-evacuation.com
18. Galea, E.R., Shields, J., Canter, D., Boyce, K., Day, R., Hulse, L., Siddiqui, A., Summerfield, L., Marselle, M., Greenall, P., The UK WTC 9/11 Evacuation Study: Methodologies used in the elicitation and storage of human factors data, 11th Interflam Conference Proceedings, London, Sept 2007, Vol 1, 2007, pp 169-181.