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Exploration of design solutions for the enhancement of crowd safety

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Abstract

The movement of large numbers of people is important in many situations, such as the evacuation of buildings, stadiums and public transport stations. Numerous incidents have been reported in the literature in which overcrowding has resulted in injuries and death during emergency situations. Modelling and empirical study of crowd safety under emergency conditions is imperative to assist planners and managers of emergency response to analyse and assess safety precautions for those situations. In this paper, we draw on the simulation tool for crowd dynamics to examine how those tools can enhance understanding about the development of safe design solutions for emergency escape. Particularly, it is shown that the adjustments of small structural features in an enclosed area can have large potential effects in terms of crowd safety.

1. Introduction

Planning and designing for safe pedestrian movements is a challenging task for managers of emergency response. Numerous incidents have been reported in which overcrowding has resulted in injuries and death during emergency situations (Still 20011). Although several models exist to describe normal pedestrian dynamics (Shiwakoti et al. 2008), quantitative theories capable of predicting such collective patterns under panic/emergency conditions are scarce due to lack of complementary data to validate model predictions (Helbing et al. 2000). That difficulty has led researchers to explore alternative means to aid in the development and validation of pedestrian models. The nature of collective behaviours as outlined in various socio-psychological literatures (Quarantelli 1957, Sime 1995) has an important role in determining the safety of pedestrian crowds. The collective patterns are not restricted to humans, but have been observed in other biological systems that display herding, flocking, schooling and swarm intelligence (Okubo 1986, Charlotte 2005). Mathematical simulation models of animal dynamics have been used since the 1970's to study the collective movements of animal (Okubo 1986). However limited attention has been directed at translating the findings observed from collective animal dynamics to the study of the collective dynamics of humans.

Shiwakoti et al. (2010, 2011) proposed a model EmSim (short for Emergency Simulation) for human crowd panic through investigation and experiments with panicking ants. The simulation model is validated for simulation of ant traffic and pedestrian traffic. For ant traffic, the model is calibrated and validated from the experimental data of panicking ants. The model parameters are then appropriately scaled up from ant traffic to the pedestrian traffic based on the scaling concept commonly used in Biology. Following that scaling, the model is applied to simulate collective pedestrian egress for the experimental scenarios as described for ant traffic. The performance of the model is also validated for pedestrian traffic based on experimental data under normal (non-panic) condition. The model was able to predict elements of the collective escape behavior. The success of the model in describing crowd dynamics of organisms that differ greatly in size, shape, and speed provided the reassurance that a model correctly identifies the essential features of solutions that are efficacious and improve the safety of pedestrians. In this paper, we explore some design solutions that may enhance the escape of individuals under emergency conditions based on further exploration of EmSim simulation model.

The paper is organized as follows. The next section briefly presents the background information on the underlying mechanisms of EmSim model. We then use EmSim model to explore some design solutions, specifically the effects on outflow of the pedestrians during emergency egress due to partial obstruction near exit, turning movements, location of exits and optimization of outflow within an escape area. The final section presents the conclusions and recommendations for future research.

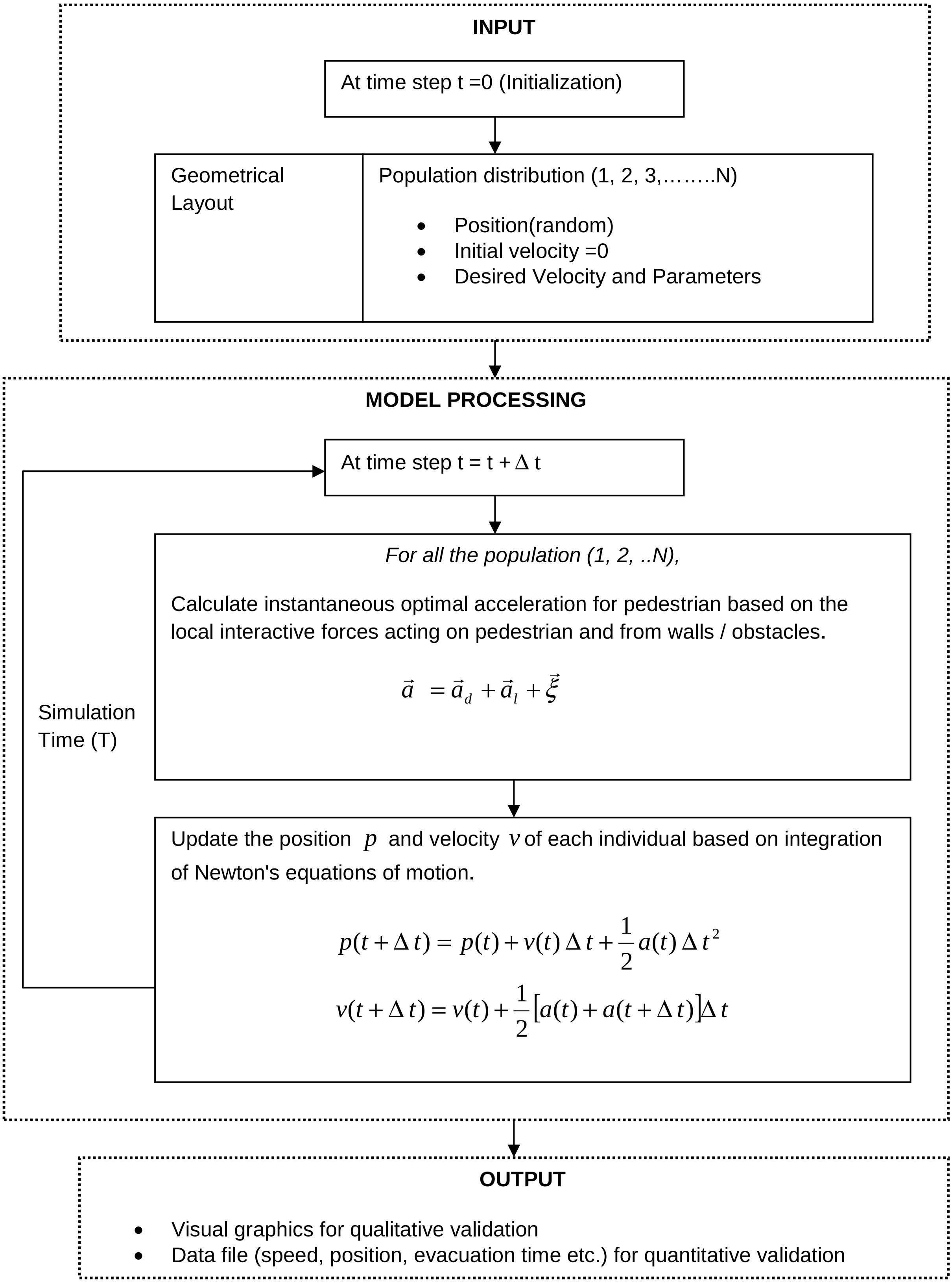
2. Simulation Model

The model EmSim proposed in Shiwakoti et al. (2010, 2011) is a two dimensional microscopic continuous model with discrete time step updating. The schematic diagram showing the operation of the simulation model is presented in Figure1. Instantaneous acceleration for each individual $(\vec{a})$ is determined by the collective forces acting on the individual. These collective forces are formulated and mathematically modeled based on empirical data from the panicking ants and modifications of the approaches used to describe collective animal dynamics and pedestrian dynamics. The collective forces basically consists of impulsive forces $(\vec{a}_d)$, local interactive forces including pushing behavior $(\vec{a}_l)$ and randomness $(\vec{\xi})$. The detailed mathematical derivation is provided in Shiwakoti et al. (2010, 2011). Given the instantaneous acceleration, the position and velocity of each individual could be updated in each time step from the integration of Newton's equation of motion.

Despite the difference in speed, size and other biological details of the panicking individuals, the model proved capable of replicating the collective dynamics of ants as well as pedestrians. To our knowledge, no single model on panic has before attempted to correlate and simulate the escape dynamics of two different entities (ants and human). There is now scope for developers of the few existing models on panic to test the extent to which their models of panic will correctly predict the escape dynamics of these two different biological entities for a given situation. Successful prediction of collective movement in both humans and ants through this model demonstrate that the model captures something fundamental about the dynamics of self-driven particles in crowds despite variation in size, manner of locomotion, cognitive abilities, and other biological traits. So, the methodology followed in developing this modeling framework is robust and unique compared to approaches adopted by other researchers.

In the next section, the simulation model EmSim is applied to gain insight on design solutions that improves the efficiency of the escape of the individuals.

Figure 1: Flow chart showing the operation of the EmSim



For all the population (1, 2, ..N),

Calculate instantaneous optimal acceleration for pedestrian based on the local interactive forces acting on pedestrian and from walls / obstacles.

$$\vec{a} = \vec{a}_d + \vec{a}_l + \vec{\xi}$$

Update the position p and velocity v of each individual based on integration of Newton's equations of motion.

$$p(t + \Delta t) = p(t) + v(t)\,\Delta t + \frac{1}{2} a(t)\,\Delta t^2$$

$$v(t + \Delta t) = v(t) + \frac{1}{2}\left[a(t) + a(t + \Delta t)\right]\Delta t$$

- Visual graphics for qualitative validation
- Data file (speed, position, evacuation time etc.) for quantitative validation

3. Exploration of Design Solutions

3.1 Partial obstruction effect

It has been reported in the literature that the placement of a partial obstruction such as a column near the exit may facilitate the flow of the people (Helbing et al. 2000) compared to the absence of the obstruction which was empirically verified by Shiwakoti et al. (2010, 2011) with the non-human biological organisms under panic conditions. However, several important points need to be considered when designing such solutions. For example, does the efficiency of the partial obstruction depend on its location i.e. the horizontal offset from the exit? Is the size of the obstacle also important? This section examines the effect of location and size of obstacle (column) for the escape of pedestrians under panic conditions.

For the simulation, two hundred pedestrians were distributed randomly in a room of 15m by 15m in size and were allowed to escape through a single door with a width of 1.2m. For the column trials, 1m and 1.5m diameter columns was placed slightly asymmetrically at a horizontal distance of 0.5m, 0.6m and 0.7m from the exit. The pedestrians were assigned a desired velocity of 5m/s which corresponded to the fleeing velocity under panic conditions reported in the literature (Helbing et al. 2000).

Figure 2 shows the snapshots of the simulation with /without a column near the exit while Figure 3 shows the average flow rate for different horizontal offsets from the exit and for different size of the column. Also a reference dotted line is drawn representing the average flow of pedestrians without any obstruction near the exit. Figure 3 highlights that the presence of a partial obstruction like a column near the exit is effective only for some horizontal offsets for a particular column diameter. Figure 3 also shows that the maximum flow rate could be different for different combinations of column size and horizontal offset. For example, the maximum flow rate for a 1.5m diameter column occurs when there is a 0.5m horizontal offset while for a 1 m diameter column the optimum offset is 0.6m. Beyond 0.7m the flow is actually below to that of the flow in case of without partial obstruction for a 1 m diameter column.

Figure 2: Simulation snapshots showing panicked pedestrian escaping from a room without partial obstruction near the exit (a) and with partial obstruction (via column) (b)

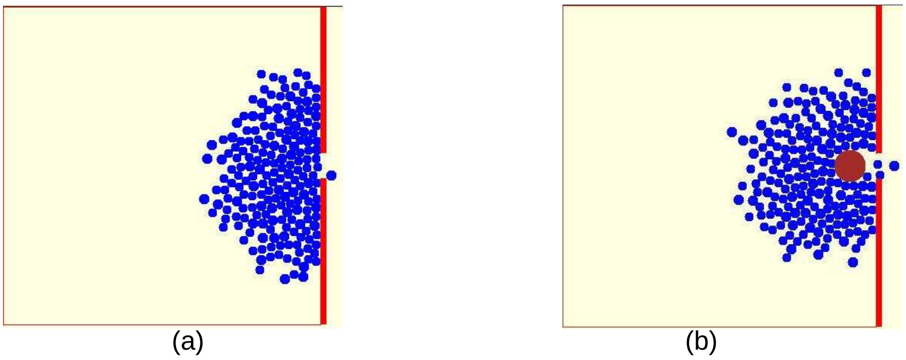
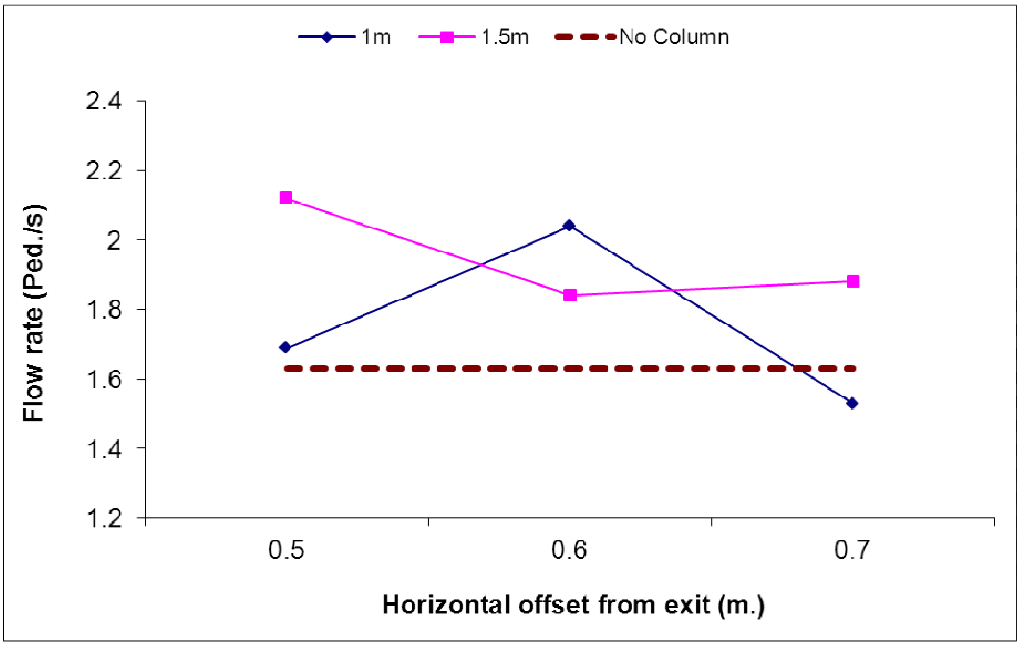

(a) (b)

Figure 3: Comparison of flow rate for different horizontal offsets for 1m and 1.5 m diameter column to that with no column scenario



The simulation results highlighted that the presence of partial obstructions such as a column near the exit do not always increase the flow of the people compared to when the column is absent. The results highlight the importance and use of simulation model in testing the effects of structural features of an escape area for controlling crowd movements.

3.2 Effects of turning movements

One of the interactions of pedestrian crowds with the physical environment during emergency evacuation is the turning movement when there is an abrupt change in the direction of the physical layout through which they escape. Previous studies on crowd disasters (Chertkoff 1999) have pointed out that when crowded pedestrians require to turn due to a change in direction (for e.g. corner, stairwells), it could lead to trampling and stampede. To illustrate the importance of avoidance of turning movement and sharp turns, simulation was conducted with EmSim for a crowd of people escaping from a bottleneck with a straight corridor and a 45 degree corridor.

For the simulation, a crowd of pedestrians was generated in an area of 10m by 8m with a bottleneck of 2m width. Upon exiting the room, people then had to pass through a corridor. Two cases (straight corridor and 45 degree turns), as explained above were considered as shown in Figure 4. In each case the corridor was the same length (10 m) and width (2 m). In the first case, the corridor was straight, 10m in length and 2 m in width. In second case, the straight corridor continued for 5m and then a connecting corridor was placed at an angle of 45 degree. The total length and width of the corridor was equivalent to that of the first case.

The simulation was conducted with different numbers of people (200 and 350) for each case. The outflow of the people at the fixed downstream end of the corridor was measured for each case. When the pedestrians in the simulation passed through the straight corridor, the collective movement was uniform in nature. In contrast, when the pedestrians passed through the 45 degree angled corridor, congestion was observed at the turning junction, creating delay in egress, as shown in Figure 4. That congestion could be the result of strong interactions and pushing behaviour due to the turning movements.

Figure 4: Snapshots of simulation for pedestrian escaping through different angled corridor: straight (0 degree) corridor (a), 45 degree corridor (b)

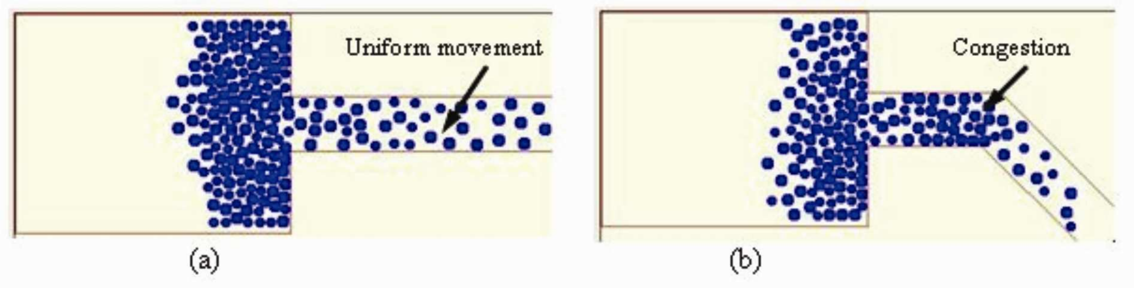
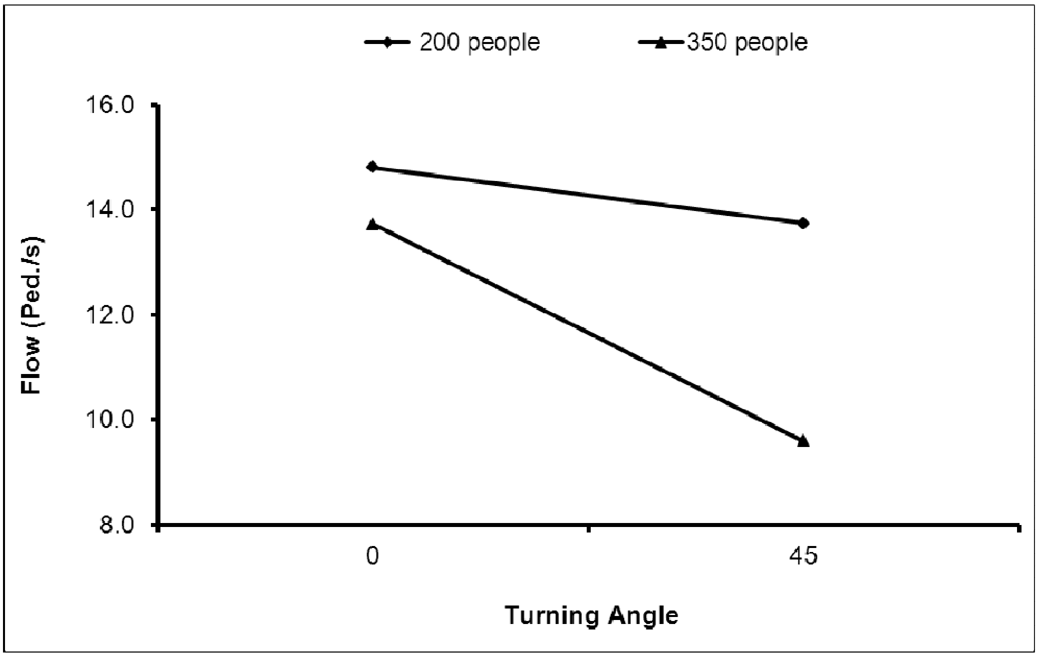


Figure 5 shows the comparison of the average flow rate of pedestrians for different densities and the turning angles. The straight corridor (turning angle =0) is much efficient compared to 45 degree turn. With the increase in pedestrian density from 200 to 350, that difference in flow rate is more pronounced. For example, the straight corridor is around 43% more efficient than the 45 degree turn for the density of 350 pedestrians compared to 8% more efficient when the density is 200 pedestrians. This suggests that the effect of turning movement is important particularly at high crowd density.

Figure 5: Comparison of flow of pedestrians for straight (0 degree) and 45 degree angled corridor



3.3 Effects of location of exits

In this section, the effects in the outflow of the pedestrians due to the location of the exits at the middle of the walls and at the corner are explored. The simulation setup was same as in the no obstruction scenario as explained in section 3.1 (Figure 3a). Figure 6 presents the simulation snapshot with the exit located at the corner. The model predicted that corner exit is more efficient compared to the exit located at the middle of the wall. Figure 7 shows the comparison of the flow for corner /middle exit scenarios based on 5 simulation trials. It can be seen that corner exit improves the flow of the people compared to middle exit. The average flow was 2.96 ped./s with the corner exit compared to 1.63 ped./s with the middle exit. Thus the presence of the exit at the corner increased the efficiency of escape by around 80%. The simulation results further supports the findings from section 3.1 and 3.2 that there are potential effects on outflow of pedestrians under panic conditions resulting from the adjustments of structural features of the escape area and the dynamics of the crowd.

Figure 6: Simulation snapshot showing panicked pedestrian escaping from a room with the exit located at corner

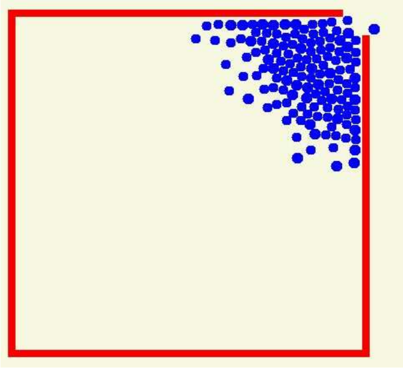
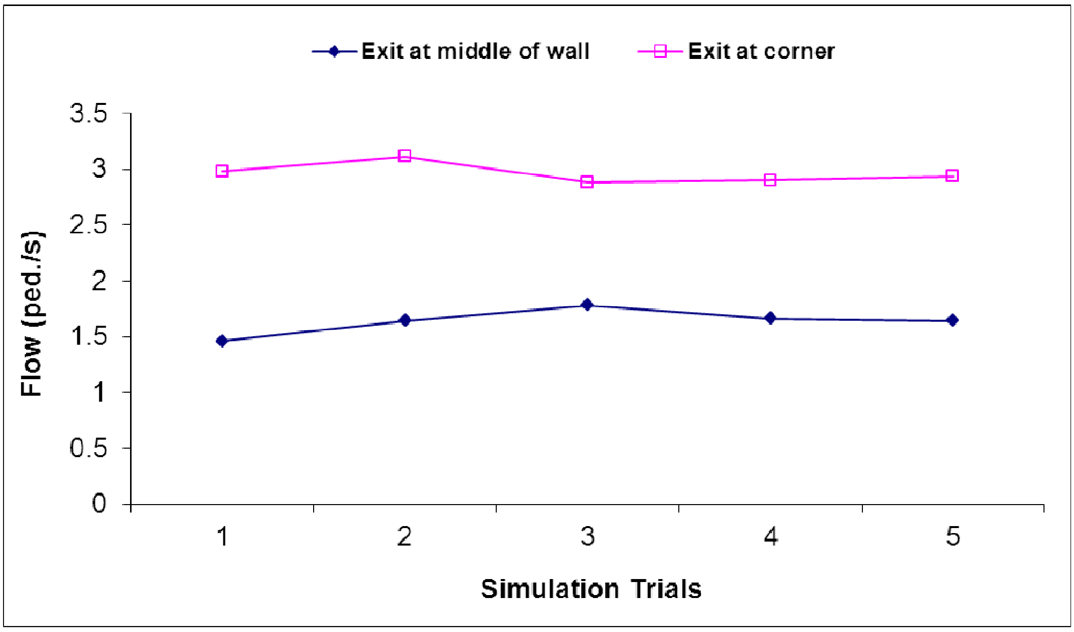


Figure 7: Comparison of flow for exit at corner / middle scenario from simuation



3.4 Optimization of outflow within an escape area

The preceding analysis suggests that there are several options for architectural /structural adjustments that optimise the escape flow within a same layout of the escape area. In this section, results from the simulations conducted for different scenarios (as described in previous sections), are used to demonstrate how an optimum design can be achieved within a given escape area.

The escape rates of people are compared for a standard case: 200 pedestrians escaping from a room (15m by 15m) with egress door width of 1.2m and with a desired speed of 5 m/s. These dimensions of the room and desired speed are consistent for the simulations conducted for pedestrian traffic in this study and hence it will be easier to compare the outflow for the same escape area and simulation conditions. The simulation results are then compared for following cases:

- Case 1: Pedestrians escaping with egress point at the middle of the walls
- Case 2: Pedestrians escaping with egress point at the corner of the walls
- Case 3: Pedestrians escaping with funnel shaped egress point
- Case 4: Pedestrians escaping with egress point at the corner of the walls and with a partial obstruction (column) present near the egress point

Table 8-1 shows the comparison of the average outflow rate for the different cases mentioned above. From the table, it can be observed that for the different cases considered, case 4 produces the maximum outflow of pedestrians. The results for case 4 highlight that the maximum escape flow of 3.71 ped./s occurs when the exit is at the corner and a column of 1.5 m diameter is located at 0.7m horizontal offset.

Table 1: Comparison of average outflow for the considered four cases

Scenarios	Average flow rate (ped./s) with no column	Average flow rate (ped./s) with column (1.5m dia.) *Horizontal offset (m.)*				
		0.5	0.6	0.7	0.8	1
Case 1: Exit at middle	1.63	n/a	n/a	n/a	n/a	n/a
Case 2: Exit at Corner	3.01	n/a	n/a	n/a	n/a	n/a
Case 3: Funnel shaped exit	2.72	n/a	n/a	n/a	n/a	n/a
Case 4: Exit at corner with column	n/a	2.70	3.22	3.71	3.08	2.88

Note: n/a = not applicable

The observed peak flow rate of 3.71 ped./s highlights that with the small architectural adjustments, it is possible improve the escape flow of the pedestrians by more than double compared to the outflow from the standard case (1.63 ped./s) of pedestrians exiting from a room with exit at the middle of the walls. This result also qualifies the conclusion that the effectiveness of a partial obstruction near the exit in fact depends on the size of the obstruction and the architectural layout of the escape area. It is not necessary that putting a partial obstruction as near to the exit as possible will improve the outflow as stated in Section 3.1 for the case of an exit at the middle of the wall. This section has thus demonstrated that with the given layout of the escape area, one can adjust the architectural elements to optimise the maximum outflow through the egress point.

4. Conclusion

Modelling and empirical study of pedestrian behaviour under emergency conditions is crucial to assist planners and managers of emergency response. In this paper, the effectiveness of different design solutions to improve the escape outflow of people was examined using insight from a simulation model. A quantitative analysis has provided insight into differing decisions about the size and location of partial obstructions near an exit, the effect of turning movements on the escape rate and the effect of location of an exit point. It was observed that the effectiveness of a partial obstruction near the exit depends on the size and location of the obstruction and the architectural layout of the escape area. It was also noted that when there is sudden change in direction of the movement of individuals moving at a high speed in a crowd, that could lead to delay in egress. Likewise, it was shown that the location of an exit at the corner can have substantial benefits in the efficiency of evacuation compared to the exit located at the middle of the walls and that there are wide range of possibilities to explore an optimum design for the escape area.

The paper has demonstrated that detailed analysis of microscopic effects would be a potentially valuable additional perspective to aid in devising solutions that are efficacious and improve the safety of the crowd. Particularly, the results indicate that the adjustments of small structural features in an enclosed area can have large potential effects in enhancing the escape of the crowd. Insight into microscopic variations would assist in advancing understanding of what properties of panic are inherent to the physical nature of the crowds, and what properties depend on the idiosyncratic details. The importance of egress design and crowd control is growing given the global trends of mass urbanization, mega-events, terrorism and natural disasters. Some of the design solutions explored in this study demonstrate the potentiality of the proposed framework to enhance crowd safety.

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