Transportation Research Part C 37 (2013) 260–267

Contents lists available at SciVerse ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Enhancing the panic escape of crowd through architectural design

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A R T I C L E   I N F O

Article history:
Received 30 April 2012
Received in revised form 11 January 2013
Accepted 23 April 2013

Keywords:
Crowd dynamics
Egress
Disaster
Biological organisms
Pedestrians
Simulation

A B S T R A C T

Doors and corridors are necessary architectural elements in public infrastructure such as transit stations, buildings and stadiums. Previous documented crowd disasters have showed that collective movement patterns are affected by the layout or the geometrical structure of the escape area. However, little study has been carried out to examine these interactions under panic situation due to scarcity of data on human panic. Here, we use bio-inspired approach to test if making appropriate architectural adjustments within a given escape area would change the collective movement patterns in a way that enhances the outflow of the crowd. First, we performed a series of experiment with ants under panic conditions to test the effect of different structural features to the panic escape in a chamber with fixed dimension. Results show that the adjustments can be effective by more than 90% in decreasing the evacuation time. We then scaled it up and simulated the situation to human scenario and found that the model prediction is consistent with those observed from the empirical data. The proposed method demonstrates that detailed analysis of microscopic effects of escape environment would be a potentially valuable additional perspective to aid in devising solutions that are efficacious and improve the safety of the crowd.

1. Introduction

Crowd safety has emerged as an important issue all around the world as there have been numerous incidents in which crowd panic has resulted in injuries and/or death. Perhaps the most critical reason for studying collective human dynamics under emergency/panic conditions is the lack of complementary data to develop and validate an explanatory model. That lack of data is most likely a major factor explaining why very few models exist which focus on panic situations. The bulk of the literature is restricted to the study of normal (non-panic) pedestrian dynamics or normal evacuation processes (Still, 2000; Hoogendoorn and Bovy, 2002; Hughes, 2003; Daamen, 2004; Antonini et al., 2006; Bandini et al., 2007; Kretz, 2007; Asano et al., 2009). Even the researchers who developed the few existing models of crowd panic have identified the need for more rigorous modeling frameworks and the development of approaches to assess the reliability of model predictions (Helbing et al., 2000).

Models of pedestrian crowds have generated a number of surprising or counterintuitive predictions. For example, panic should induce "symmetry breaking" in which some available exits or escape routes from enclosed spaces are jammed while others go under-utilized (Helbing et al., 2000). This phenomenon is known to occur in human crowd disasters (Helbing et al., 2000), and has been demonstrated in experimental groups of the panicked leaf-cutting ant (Altshuler et al., 2005). Models also predict a very surprising prediction that escape rates will be enhanced if there is a partial obstruction or barrier on the

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http://dx.doi.org/10.1016/j.trc.2013.04.009

"upstream" side of an exit (Helbing et al., 2000). This counterintuitive performance of the obstacle near an exit has also been the subject of interests for researchers working on granular matters (Alonso-Marroquin et al., 2012) and architecture (Escobar and Rosa, 2003; Illera et al., 2010) However, the results could not be verified due to the lack of data on human panic. Shiwakoti et al. (2010, 2011) demonstrated these phenomena through experiments with panicking Argentine ants and a developed model EmSim. Review and discussion about usefulness and limitations of these non-human biological organisms in understanding pedestrian crowd panic can be found in Shiwakoti and Sarvi (2013).

Given this indication that seemingly small structural features of the physical environment can have disproportionate influence on the panic escape dynamics, it may have enormous potential in the design of optimal layout of the escape area. This is clearly a major challenge for research in this field since it is clearly impractical to create experimental conditions with human where these circumstances can be studied. In this paper, we examine how the egress time of the individuals can be minimized from a given layout of escape area by merely adjusting the architectural features. We follow a methodology involving experiments with ants under panic condition and a use of crowd simulation model. The use of term panic and emergencies in this study refer to situations in which individuals have limited information and vision (due to high crowd density and short time for egress), and which result in physical competition and pushing behavior. That is different from the meaning of the term that most social scientists have used, i.e., "panic" is restricted to instances when both high emotional arousal and irrational behavior occur.

1.1. Background

Shiwakoti et al. (2010, 2011) performed experiments with Argentine ants to study the effect of with and without a partial obstruction near the exit in a circular chamber. It was reported that the presence of a partial obstruction (via a column) at the exit generally enhanced (by around 44%) the flow of panicking ants as compared to absence of the obstruction. Shiwakoti et al. (2011) conducted another series of experiments with ants to study the effect of location of the exit on the collective movement patterns of non-human entities during rapid egress. Two scenarios were considered: ants escaping from a square chamber with exit at the middle of the side walls versus exit at the corner. It was reported that corner exit was effective (by around 58%) in increasing the outflow of ants compared to exit at the middle. With these empirical results, Shiwakoti et al. (2010, 2011) developed a model EmSim that could capture the fundamentals of crowd panic between ants and human; the two types of organisms that differ in the manner and speed of locomotion, in chemical, visual and aural perception and communication, and in the nature of their social organization. The model parameters were scaled up from ants experiment to human situation through the scaling concept used in Biology and were validated for normal and panic situation (Shiwakoti et al., 2011). Since the experiments were conducted on different shape of chambers (circular and square), it is not possible to study or generalize the effect on the outflow due to different architectural adjustments (partial obstruction vs. no obstruction vs. corner vs. middle exit) in a given chamber (of fixed shape and size). Thus, in this study, we conducted series of experiments with Argentine ants under panic condition in a chamber of fixed shape and size and tested several structural adjustments in the chamber that could influence the panic escape. We then scaled it up and simulated the situation to human scenario for a variety of design solutions using EmSim simulation model.

2. Experiments with ants

We conducted experiments with colony fragments of around 200 Argentine ants housed at ambient temperature in square wooden chambers measuring 31 mm by 31 mm and 4 mm deep. Keeping the dimensions of the chamber fixed, we then made four architectural adjustments in the chamber:

- exit at the middle of the wall,
- exit at the corner,
- exit at the middle with a partial obstruction (via a column) near the middle exit and
- exit at the corner with a partial obstruction near the corner exit.

We treated the exit at the middle of the wall as a standard design so that the relative effectiveness of other design can be compared to this standard design. The chamber had a single exit 2.5 mm wide and 2.0 mm high. The column was 5 mm in diameter and 4 mm high (floor-to-ceiling) and was placed inside the chamber 2 mm in front of the exit. In each experimental trial, we induced rapid evacuation by injecting 10 μl of citronella oil (insect repellent) into the chamber; similar process as followed by Shiwakoti et al. (2010, 2011). We conducted 5 replicates of each treatment condition. Fig. 1 shows the schematic diagram of the experimental setup for the square chamber experiments with an exit located at the corner of the walls or at the middle of the wall, as well as with partial obstruction in the form of a column near the middle or corner exit.

We video recorded the escapes using a digital video camera, and later extracted the exit time (to the nearest 0.04 s) of the first 50 ants to leave the chamber. From these data, we reconstructed the cumulative time-versus-escape sequence pattern.

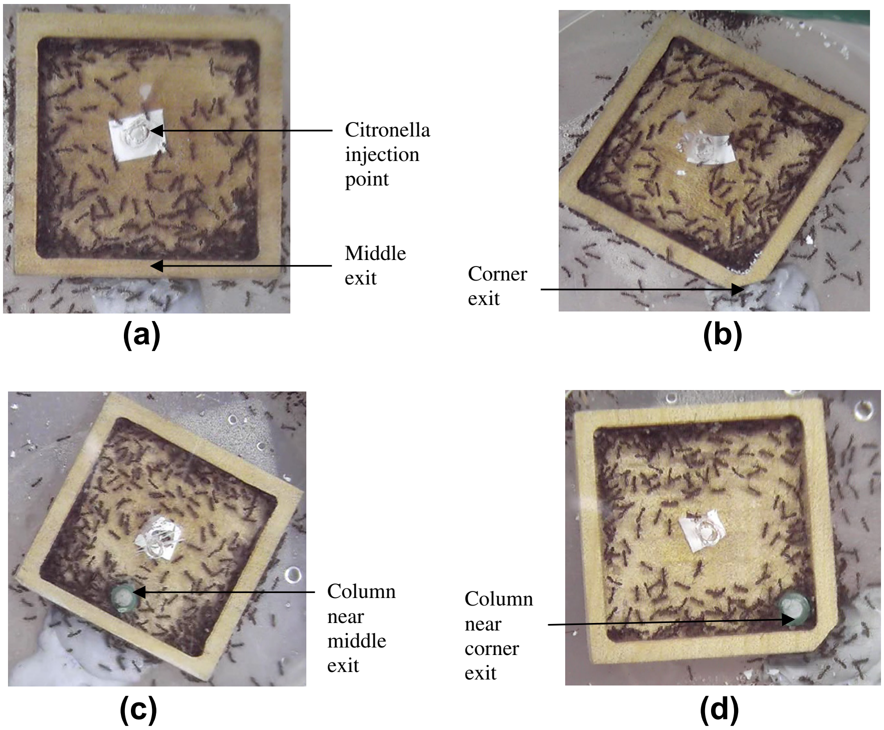

Fig. 1. Experiments with panicking ants: exit located at the middle of wall (a), exit located at the corner (b), column near middle exit (c) and column near corner exit (d).

2.1. Data analysis

It was observed that the adjustments of small structural features in the chamber had a significant effect in reducing the evacuation time of the ants compared to the standard design. The average evacuation time for different experimental scenario are shown in Table 1. The location of exit at the corner was almost twice effective (93.5%) in reducing the egress time compared to the exit at the middle of the walls. Similarly, the presence of partial obstruction near the middle exit or at corner exit were very effective in reducing the evacuation time (30.3% and 67.7% respectively) as compared to the exit at the middle of the wall. These results were highly significant as revealed by *F*-value and *P*-value from ANOVA test ($F_{3,16} = 14.40$, $P < 0.001$). Another very surprising result that was noticed is the differing performance of partial obstructions near the exit. While the presence of column near a middle exit was superior compared to middle exit; but its performance was not effective when compared to exit at the corner (67.7% vs. 93.5%, Table 1).

Fig. 2 shows the comparison of the cumulative time-versus-escape sequence pattern for the first 50 ants for different experimental scenarios. Each trace shows an individual simulation trial. First, it is clear that the escape rate for the considered four experimental scenarios is quantitatively different, although variation among trials with corner exit and column near corner exit seems lower than that of the middle exit or column near the middle exit. Second, the superior escape rate with a corner exit or column near the corner exit is established early and maintained throughout the escape sequence compared to the middle exit or column near the middle exit. Third, it is interesting to note that there is overlap in escape sequences between the middle exit and column near the middle exit treatments, so that the advantage due to the partial obstruction near an exit is an average effect. Similar overlapping in escape sequences can be observed between the corner exit and column near the corner exit treatments.

Table 1
Mean escape time for first 50 ants for each treatment condition.

Experimental scenario	Escape time for first 50 ants (s)		Relative effectiveness compared to standard design (%)
	Mean	Standard deviation	
1. Exit at the middle of the wall (standard design)	18.22	1.97	–
2. Exit at the corner	9.42	0.68	93.5
3. Middle exit with column	13.98	3.97	30.3
4. Corner exit with column	10.86	0.95	67.7

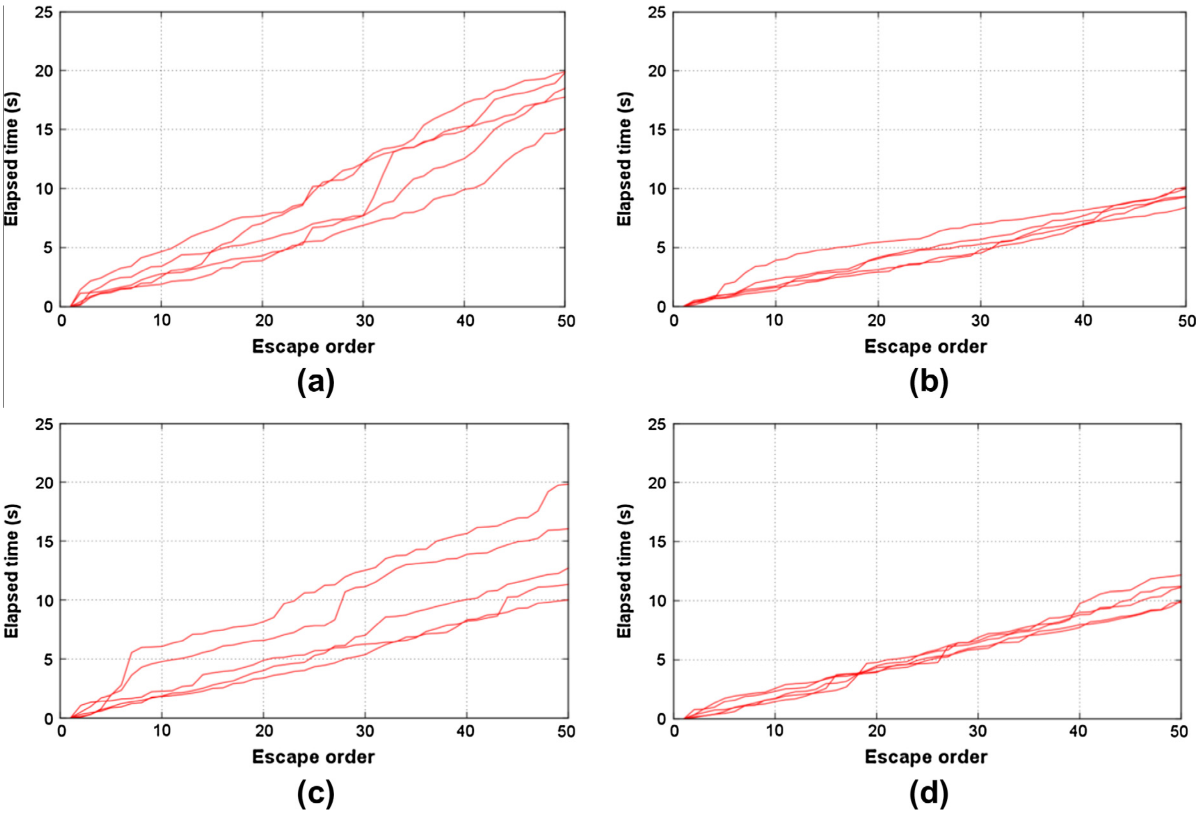

Fig. 2. Escape pattern distribution of panicking ants: middle exit (a), corner exit (b), middle exit with column (c) and corner exit with column (d). Each trace shows an individual experimental trial.

The enhanced panic escape due to the column or corner exit could be due to the minimization of conflict points at the egress point. With a middle exit, ants escaping along both sides of the wall had to change their direction at the exit in order to evacuate. That resulted in conflicts with the ants that were moving straight towards the exit. However, in the case of column present or the corner exit scenarios, there was comparatively less conflicts with ants that were moving straight towards the exit and the ants escaping from the side walls. The barrier may also absorb physical pressures from a dense crowd and disrupt the formation of transiently "frozen" crowd configurations that momentarily prevent egress.

3. Simulation of pedestrian crowd

The results from ant experiments suggests that the structural features in an escape area may facilitate or hinder the escape of a crowd. Mirroring the scenarios considered in the ants experiments, simulation of pedestrians under panic were considered for cases with/without a column near the middle exit or corner exit of a room using the EmSim model developed by Shiwakoti et al. (2010, 2011). In the following sections, we present a summary of EmSim model and then present the results from the simulation.

3.1. Model

Collective movement in EmSim model is governed by Newtonian mechanics. The model identifies two kinds of internally generated forces. The first is a global impulsive force that defines an intended path. The second is a local force whose strength and direction varies with the proximity and arrangement of other individuals in the crowd. A final component force arises when individuals in the crowd come into contact with each other or with features of their environment. Thus, the net force on individual i is given by

$$\vec{F}_i = \vec{F}_I + \vec{F}_L + \vec{F}_C \tag{1}$$

$$\vec{F}_i = \left[m_i v_f \sigma^{-1} \underset{i}{\vec{p}}\right] + \left[\phi W(\theta_{ij}) \left(\frac{X_{ij} - (r_i + r_j) - \lambda_R}{[X_{ij} - (r_i + r_j) - \lambda_R]^2 + \lambda_A^2}\right) \vec{n}_{ij}\right] + \left[\alpha_1 \vec{v}_n + \alpha_2 \delta \vec{n} + \mu_1 \vec{v}_t + \mu_2 \delta \vec{t}\right] \tag{2}$$

where $\vec{F}_I$ = impulsive force. The impulsive force is composed of a characteristic speed, v_f, mass m_i, a unit vector $\vec{p}_i$ and a relaxation time σ^{-1}. $\vec{F}_L$ = local interaction forces. The local interactive forces are modeled as an interplay of attraction and repulsion governed by the distance X_{ij} between individuals (accounting the body size with radius r_i and r_j), a range λ_A of separation and a range λ_R of repulsion. $W(\theta_{ij})$ represents the weightage function that give greatest weight to individuals or obstacles directly ahead along an individual's desired path, $\vec{n}_{ij}$ is a unit vector normal to the *ij* axis, and the parameter ϕ can take on one of two values depending on whether $X_{ij} - (r_i + r_j) - \lambda_R$ is positive (and the attractive force is in play) or negative (for the repulsive force). $\vec{F}_C$ = contact force. The contact force is modeled as dissipation of the collision energy by the "spring" and as such determined by a damping coefficient, α_1, and the normal component of the impact velocity, $\vec{v}_n$. The rebound in the normal direction $\vec{n}$ is governed by the compression δ and an elastic restoration coefficient α_2 that reflects the stiffness of the particles in contact. The tangential force is similarly governed by friction coefficients, μ_1 and μ_2, the tangential component of the impact velocity, $\vec{v}_t$, and the compression δ and tangential vector $\vec{t}$.

Avoidance of physical obstacles in the environment and the effect of contact between individuals and stationary obstacles is modeled by an expression analogous to $\vec{F}_L$ and $\vec{F}_C$.

3.2. Simulation setup

Two hundred pedestrians were distributed randomly in a room 15 m by 15 m in size and were allowed to escape through a single door with a width of 1.2 m. For the column trial, a 1.5 diameter column was placed near the exit at a distance of 0.5 m from the exit. The desired velocity of 5 m/s was assigned for each individual as it corresponded to the fleeing velocity under panic conditions reported in the literature (Helbing et al., 2000). The body size of pedestrians was reflected through the distribution of shoulder widths which is represented in the simulation model by the diameter of a circle for each entity.

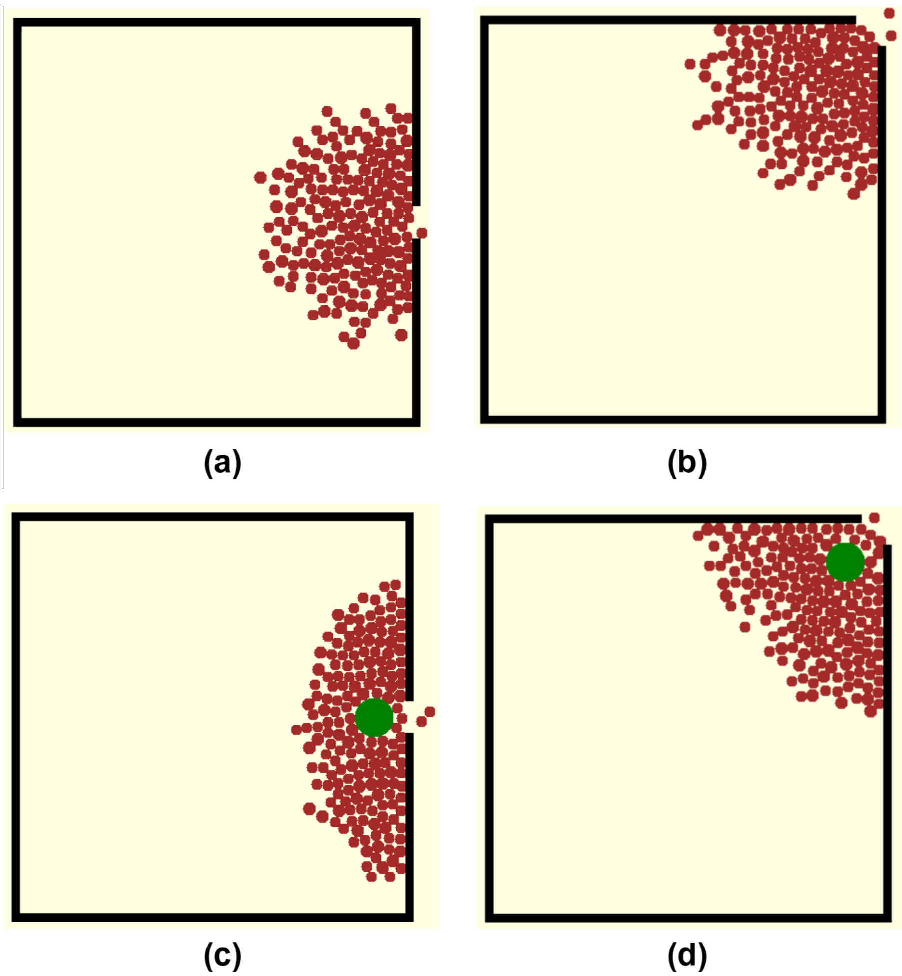

Fig. 3. Simulation snapshots showing panicked pedestrian escaping from a room with middle exit (a), corner exit (b), middle exit with column (c) and corner exit with column (d).

Body size range between 0.4 m and 0.5 m in the simulation was considered as they represent the common range in the anthropometric surveys conducted around the world (Pheasant and Haslegrave, 2006). Fig. 3 shows the snapshots of the simulation for the considered four scenarios. We conducted five simulation trials for each scenario.

3.3. Simulation results

Consistent with the experiments from panicking ants, the simulation model predicted that the adjustments of structural features within an escape area had an effect on the collective movement of the pedestrian crowd. Table 2 shows the average evacuation time for the four scenarios. The location of exit at the corner reduced the evacuation time by more than double (121.1%) compared to the exit at the middle of the walls.

Similarly, the presence of a partial obstruction near the middle exit or at the corner exit were very effective in reducing the evacuation time (35.5% and 87.2% respectively) as compared to the exit at the middle of the wall. These reductions in evacuation time are comparable to those observed in ants experiment in Section 2.1 (Table 1).

The comparison of the cumulative time-versus-escape sequence pattern for the first 50 pedestrians similarly showed the consistency with the escape rate curve observed from the ants experiment. Fig. 4 shows the comparison of the escape rate curve from the simulation for different scenarios.

Table 2
Mean escape time for first 50 pedestrians for each treatment condition.

Experimental scenario	Escape time for first 50 pedestrians (s)		Relative effectiveness compared to standard design (%)
	Mean	Standard deviation	
1. Exit at the middle of the wall (standard design)	30.52	2.98	–
2. Exit at the corner	13.80	1.10	121.1
3. Middle exit with column	22.52	3.46	35.5
4. Corner exit with column	16.30	1.43	87.2

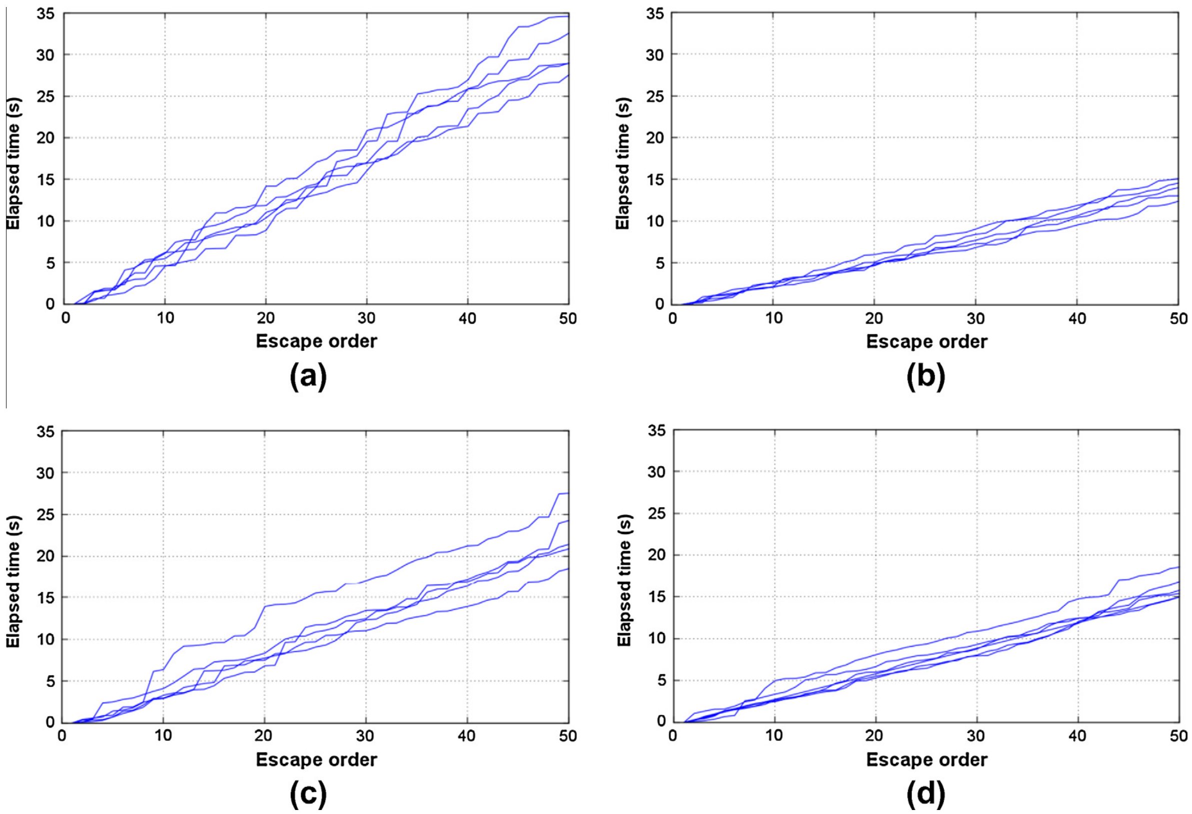

Fig. 4. Escape pattern distribution of panicking pedestrians: middle exit (a), corner exit (b), middle exit with column (c) and corner exit with column (d). Each trace shows an individual simulation trial.

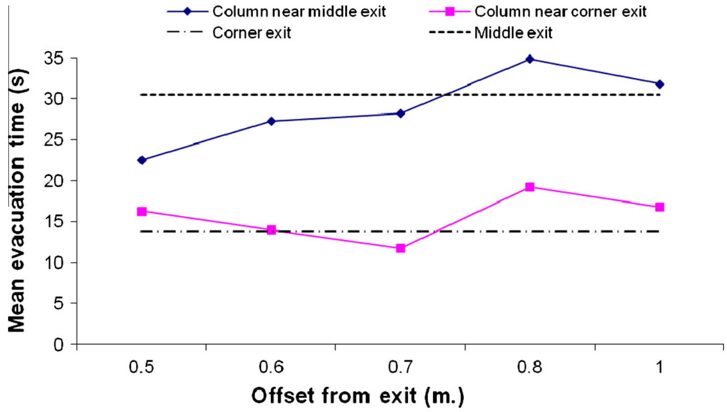

Fig. 5. Comparison of mean evacuation time showing the effects of partial obstruction for different offset from the exit. Two horizontal lines represent as a reference for comparison with middle exit and corner exit respectively.

As in ants experiments, the escape rate curves for each treatment condition is quantitatively different and variation among trials with/without column near the corner exit is lower than that of with/without column near the middle exit. Also the superior escape rate with the corner exit or column near the corner exit is established early and maintained throughout the escape sequence compared to the middle exit or column near the middle exit. Overlapping in escape sequences is also noticeable in Fig. 4.

3.3.1. Effect of partial obstruction location

From Tables 1 and 2, it is clear that the presence of partial obstruction near the middle or the corner exit reduced the egress time for both ants and pedestrians as compared to the standard situation of exit at the middle of the wall. Also, it showed the differing decisions about the performance of a partial obstruction near an exit (as discussed in Section 2.1). We further examined whether the performance of the partial obstruction depend on its location (i.e. offset distance from the exit) through simulation. For that, we conducted another series of simulation trials with column placed near the middle exit or the corner exit at different offset distance from the exit; 0.6 m, 0.7 m, 0.8 m and 1 m respectively and compared their performance with the previous results obtained in Section 3.3 (Table 2).

Fig. 5 shows the comparison of the performance of these adjustments for panicked pedestrians leaving the room. Fig. 5 shows that the effectiveness of the partial obstruction near an exit is indeed dependent on its location. For example, the presence of column near the middle exit is effective in reducing evacuation time only up to 0.7 m offset as compared to the middle exit. Beyond 0.8 m, the presence of column near the middle exit actually increases the evacuation time as compared to the case of absence of column near the middle exit. In the case of with/without column near the corner exit, the situation is contrary to the case of with/without column near middle exit. The performance of the column near the corner exit was ineffective up to 0.6 m offset as compared to the case of absence of the column near the corner exit. However, there was dramatic decrease in evacuation time when the column was placed at an offset of 0.7 m from the corner exit and beyond 0.8 m, the presence of column was again ineffective as compared to the corner exit. Overall, the most effective design among the various design considered for the given room (as shown in Fig. 5) was the presence of the column near the corner exit at the offset distance of 0.7 m. This would result in more than 2.5 times effectiveness (160%) in reducing the egress time as compared to the standard design of exit at the middle of the wall (11.77 s vs. 30.52 s).

The results as observed above qualify the observations noted in ants experiment (in Section 2.1) that the effectiveness of the partial obstruction near an exit depends on the location of the obstruction and the layout of the escape area. It appears that the partial obstruction generally reduces the conflicts among individuals near the exit by channelizing the flow. Also, the extra pocket of space evolved due to offset from exit create relatively less conflicts and hence reduced crowd pressure near the exit. However, the optimal performance of this extra space needs further investigations in future. Nevertheless, by crossing large scales of body size and other parameter values (between ants and human), these results imply that perhaps there may be common underlying dynamics to the collective behavior of self-driven particles across a wide size range.

4. Conclusions

The importance of egress design and crowd control is growing given the global trends of mass urbanization, mega-events, terrorism and natural disasters. In this paper, the effectiveness of different design solutions to improve the escape outflow of people was examined using insight from experimental data on social insets such as ants and a crowd simulation model. It was demonstrated that careful design of small structural features could have significant effects on pedestrian traffic outflow.

A decrease in the evacuation time by more than 160% compared to the evacuation time in a standard situation can be achieved with small architectural adjustment in a given escape area.

The paper has demonstrated that with the given layout of the escape area, one can adjust the architectural elements to optimize the maximum outflow through the egress point. Insight into such 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. Some of the design solutions explored in this study demonstrate the potentiality of the proposed framework to enhance crowd safety. With this approach, it is possible to study a variety of scenarios, potential problems, their consequences, and the outcome and effect of collective dynamics. In the future, there is need to further examine the physical and behavioral similarities and dissimilarities among these different biological entities and how they may help to develop clever design solutions that could enhance the crowd safety.

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