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A comparative study of pedestrian crowd flow at middle and corner exits

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Abstract

Bottleneck formed due to complex architectural configurations can create hazardous situations for pedestrian crowd as have been noted from the previous documented studies of crowd disasters. Existing studies demonstrate that escape layout and adjustment of architectural features in an escape area can have an effect on the outflow and safety of the pedestrian crowd. However, all the observed results are either the mathematical prediction or empirical experiments with non-human organisms. There is lack of empirical data on human crowds that explores the effect of architectural configurations on the outflow of the people. This is critical for verification of the model intended to simulate the pedestrian crowd behaviour in built environment such as train stations, stadiums and shopping malls.

In this paper, the comparative performance of location of two exits (middle vs. corner exit) is explored with 50 human participants in a controlled laboratory egress experiments under normal walking and slow running (faster walking) conditions. Each set of experiment was repeated for three times and a total of 12 experimental trials were conducted. It was observed that compared to middle exit, corner exit was efficient in terms of outflow by around 8.7% under normal walking condition and around 4.2% under slow running or faster walking condition. Further, it was observed that with corner exit, there were less long headways (successive time gap between two pedestrians) and potential conflicts as compared to middle exit. The findings from this paper have demonstrated that there is a scope to adjust the architectural elements to optimize the maximum outflow and enhance the pedestrian crowd safety at the egress point. Further the output from the experiments can be used to develop and verify mathematical models intended to simulate pedestrian crowd evacuation.

1. Introduction

Over the past few decades, pedestrian crowd safety has emerged as an important issue to planners and managers of emergency response all around the world. There have been numerous incidents in which crowd stampedes and evacuation have resulted in injuries and/or fatalities (Shiwakoti et al., 2008; Shi et al., 2015). The movement of large numbers of pedestrians in complex built environment such as major train stations, stadiums, shopping malls and open events is important from safety and daily operations point of view. Particularly transport hubs pose a significant challenge in the management and security of a large volume of passengers during special events and unexpected service disruptions (Fridolf et al., 2013; Pender et al., 2013; Pender et al., 2014; Shiwakoti et al., 2016, 2017). As such different approaches ranging from socio-psychological studies (Chertkoff and Kushigian, 1999; Kobes et al., 2010), mathematical/engineering models (Helbing et al., 2002;

Daamen 2004;, Shiwakoti et al., 2008) and animal models (Shiwakoti et al., 2011a; Garcimart´ın et al., 2015) have been followed in the literature to understand the crowd dynamics and develop appropriate design solutions that can enhance the outflow and safety of the people under normal and emergency situation. Noting the advantages of questionnaire survey in transport mode choice analysis (Zheng et al., 2014), recently researchers have also looked into questionnaire survey to understand the likely behaviours of passengers as well as passenger's perceptions and ratings of emergency evacuation procedure in train station under emergency condition (Shiwakoti et al., 2016, 2017).

Corridor and door egress flow have been considered as an important element in architecture design, pedestrian flow organization and crowd safety management, under both normal and emergency situations (Helbing et al., 2005; Shiwakoti et al., 2011a; Shiwakoti et al., 2015, Shi et al., 2016). Bottleneck formed due to complex architectural configurations can create hazardous situations as have been noted from the previous documented studies of crowd disasters (Chertkoff and Kushigian, 1999). Exit points in train stations, shopping malls and stadiums are often regarded as bottlenecks that impede the outflow of people. Particularly, under emergency evacuations, pedestrians usually move faster and may push each other when egressing through an exit. Given that such collective behaviours could potentially lead to crowd turbulence resulting in crowd accident such as stampede (Helbing et al., 2005), it is important to understand the performance of these architectural features and develop appropriate design solutions.

Models of pedestrian crowds have generated a number of counterintuitive predictions. For example, panic in human crowds 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., 2002). This phenomenon has also been demonstrated in experimental groups of the panicked leaf-cutting ant (Altshuler et al., 2005) and Argentine ants (Shiwakoti et al., 2010). Models also predict a very surprising prediction that escape rates will be enhanced if there is a partial obstruction or barrier on the "upstream" side of an exit (Helbing et al., 2002). This counterintuitive performance of the obstacle near an exit has also been the subject of interests for researchers working on granular matters (Zuriguel et al., 2011) and architecture (Escobar and Rosa, 2003; Illera et.al., 2010). Given that it is infeasible to perform experiments with humans in real panic conditions for ethical reasons, researchers have followed an alternative pathway by conducting experiments using non-human biological organisms. For example, Shiwakoti et al. (2010, 2011a) pioneered the 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 consistent with the model's prediction for human crowds, presence of a partial obstruction (via a column) at the exit generally enhanced the flow of panicked ants as compared to absence of the obstruction. However, Shiwakoti et al. (2014) also noted that the partial obstruction does not always increase the outflow and that the performance of the obstruction depends on the size of the obstacle and the distance from the exit.

Shiwakoti et al. (2011a; 2013) conducted another series of experiments with ants to study the effect of location of the exit on the outflow during rapid egress. Two scenarios were considered: ants escaping from a chamber with exit at the middle of the side walls versus exit at the corner. It was reported that corner exit was effective in increasing the outflow of ants compared to exit at the middle. Further, the simulation study on human crowds evacuation by Shiwakoti et al. (2014) demonstrate that demonstrate that corner exit is efficient in terms of outflow of pedestrians as compared to middle exit. However, this is only a mathematical prediction and has not been verified with empirical data with human subjects.

In summary, there are existing studies that demonstrate that escape layout and adjustment of architectural features in an escape area can have an effect on the outflow and safety of the pedestrian crowd. However, all the observed results are either the mathematical prediction or empirical experiments with non-human organisms. There is lack of empirical data on human crowds that explores the effect of architectural configurations on the outflow of the people.

Therefore, the aim of this paper is to observe the effect of the exit location in terms of outflow and safety of pedestrian crowd flow through controlled laboratory experiments with human participants. Similar to ants experiment conducted by Shiwakoti et al. (2011a; 2013), the comparative performance of location of two exits (middle vs. corner exit) is explored in this paper with human participants under normal walking and slow running (faster walking) conditions. This is critical to verify or negate the conclusions derived from the study of collective behaviour of non-human organisms and the simulation studies of human crowds.

The paper is organized as follows. The next section presents the description of the controlled laboratory experiments. Subsequent sections then describe the data analysis and key results. The final section presents the conclusions and recommendations for future research.

2. Experiments

2.1 Experiment setup

The experiments were performed at a hall in Southeast University Graduate School in Suzhou, China in August, 2015. A total of 50 college students were selected as participants for the experiment. College and university students have been widely used as participants for controlled walking laboratory experiments in the past (Helbing et al., 2005; Shiwakoti et al., 2008). However, the inclusion of different age distribution and general population as participants is desirable. Nevertheless, our conclusions are based on relative flow values rather than the absolute values and hence may not have significant impact on the output. The students were selected from different classes and as such were not familiar with each other. This is important to minimise the external effect on outflow due to familiarity with each other.

For the experiment, two experimental setups were designed (as shown in Figure 1 a & b):

(i) A room (8 m by 8 m) with an exit located at the middle of the wall. The width of the exit was 1.2 m. The room was created through the use of desks. The use of desks and chairs or ropes to create an experimental setup is quite common for controlled laboratory experiments with pedestrians (Helbing et al., 2005; Shiwakoti et.al, 2015). The participants were located at 2 m away from the exit.

(ii) Same room setup as in (i) except that the exit was located at the corner. The width of the corner exit was similar (1.2 m).

The snapshots from the experiments can be seen in Figure 1 (c & d). With 50 participants walking in the room 8 m by 8m, it was enough to create a stable and congested flow situation at Level of Service (LOS) E (HCM, 2000).

2.2 Conduction of experiment

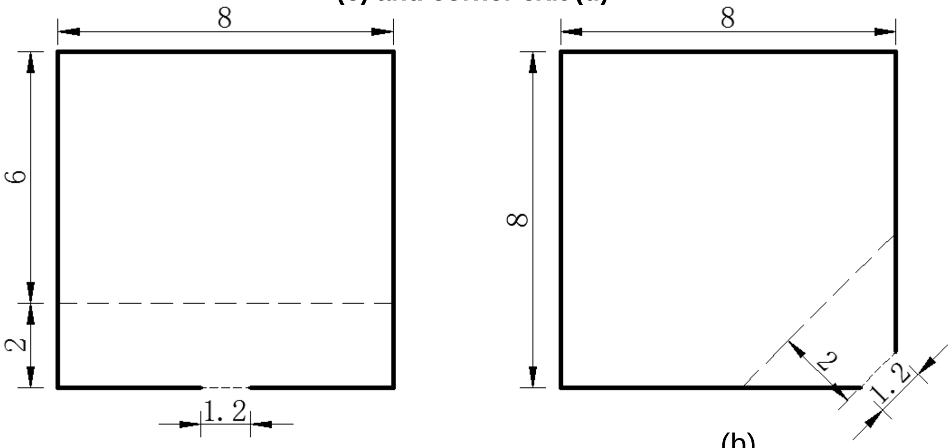
Participants were held separately behind a waiting line (2 m away from the exit) before starting to escape through the exit. Participants were provided with coloured hats for better visualization during data extraction. Before the start of the experiments, participants were instructed that they should walk normally or run slowly as per the instruction and pass through the exit. However, no information was provided to the participants regarding the research aims of the study. Few warm up walking trials were conducted to ensure that participants were comfortable in walking through the exit and follow the instruction.

Each set of experiment was repeated for three times. With two desired speed for walking operations (normal and faster walking), total of 12 experimental trials were conducted. In order to minimize the effect of tiredness, participants rested for a while and drink some water for replenishment when 6 trials finished.

A whistle signal was used to initiate the walking and the participants returned to the waiting area for next repetition after all of the participants have passed through the exit. To minimise the cumulative learning behaviour of participants, the position of the individuals within the group was randomly located for the next trial.

Participants were first asked to walk with their normal walking speed and the experiments were conducted for three repetitions. After that, participants were asked to walk faster (slow running) and the experiments were repeated three times similar like normal walking. While normal walking would be relevant to the congested situation in day to day pedestrian activities or special events, slow running or faster walking may be more representative when people are in hurry (as observed during peak hour in train stations) or in normal evacuation process (Daamen, 2004). The experiments were recorded via two HD video cameras. One camera was placed in front of the exit to capture the flow while the other one was set at the side to look into how people try to get out of exit.

Figure 1: Experiment layout of middle exit (a) and corner exit (b), snapshots from middle exit (c) and corner exit (d)



(a) (b)

(c) (d)

2.3 Data extraction

Relevant data on pedestrian escape time and headway (time gap between successive pedestrians) were extracted using a video tracking software named Tracker (Brown, 2014).

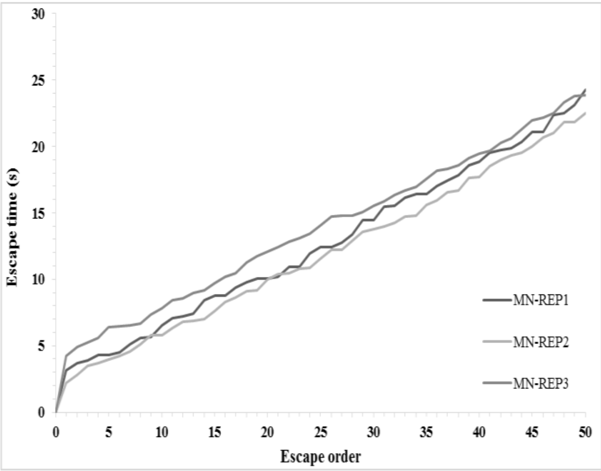
This software has been widely used in video modelling and analysis researches including pedestrian trajectory analysis (Shi et al., 2016).

3. Data analysis

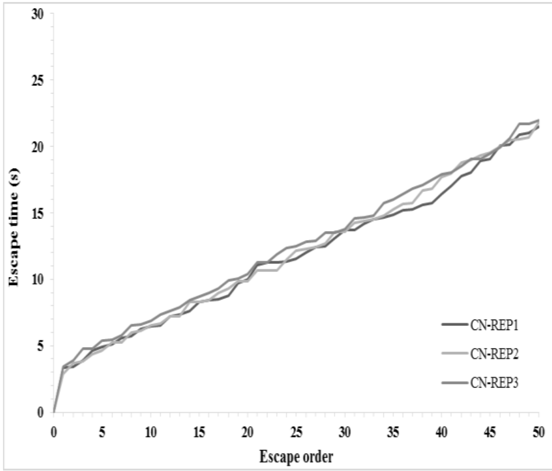
3.1 Escape order

The cumulative time-versus-escape sequence pattern for each trial in the two treatment groups (corner or middle exit) is presented in Figure 2 while the comparison of average escape time is presented in Table 1.

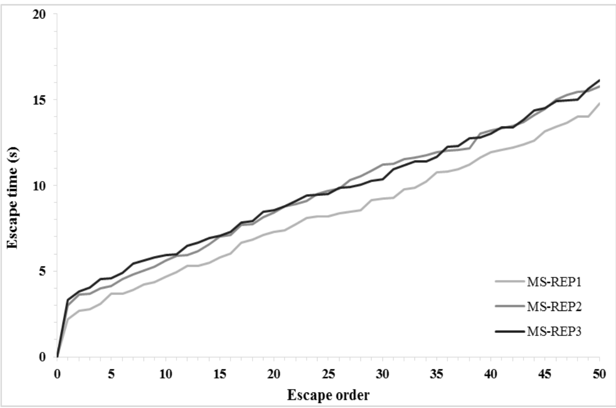
Figure 2: Plot of escape rate curve: (a) middle exit normal walking (MN), (b) corner exit normal walking (CN), (c) middle exit slow running (MS) and (d) corner exit slow running (CS)



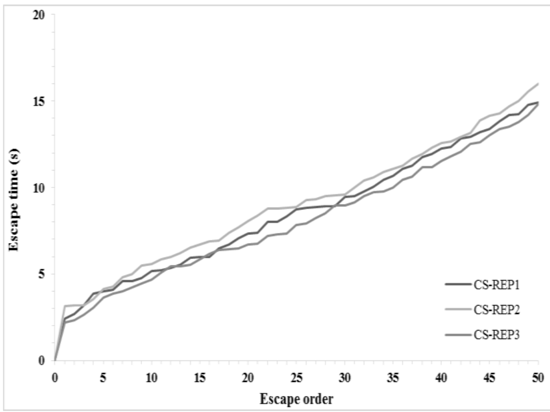
(a)



(b)



(c)



(d)

Some comparisons are available by inspection of Figure 2. First, it is clear that the variation among trials seems lower in the corner exit as compared to middle exit for both normal walking and slow running. Second, the superior escape rate with a corner exit is, on average, established early and maintained throughout the escape sequence. As can be seen from Table 1, with a corner exit, evacuation times for the 50 people ranged from 21.52 s to 22 s (mean $\pm$ s.d = 21.04 s $\pm$ 0.21 s), while in middle exit, evacuation times ranged from 22.48 s to 24.24 s (mean $\pm$ s.d = 22.64 s $\pm$ 0.39 s) for normal walking. The corresponding results for the faster walking were 9.84 s to 10.16 s (mean $\pm$ s.d = 14.37 s $\pm$ 0.72 s) with the corner exit, and 9.76 s to 10.88 s (mean ± s.d = 14.92 s ± 0.51 s) with the middle exit. Hence, compared to middle exit, corner exit was efficient in terms of outflow by around 7.6% under normal walking condition and around 3.8% under slow running or faster walking condition (if initial and last 5 participants were neglected to minimise the effect of initialisation, the corresponding efficiency in the outflow were 8.7% and 4.2% respectively. It can be expected that with greater number of people and realistic boundary materials, reduction in evacuation time due to corner exit could be substantial.

Table 1: Comparision of average esape time for middle exit and corner exit for normal walking and slow running condition

Experimental scenario	**Normal Walking**			**Slow Running**		
	Escape time for 50 pedestrians (s)		Relative effectiveness (%)	Escape time for 50 pedestrians (s)		Relative effectiveness (%)
	Mean	Standard deviation		Mean	Standard deviation	
1. Middle exit (standard design)	22.64	0.39	-	14.92	0.51	-
2. Corner exit	21.04	0.21	7.60	14.37	0.72	3.83

3.2 Safety analysis

Headway distribution is important for the evaluation of emergency egress strategies and safety, as it can reflect the time gap between pedestrian crowds to examine clogging at the bottlenecks. Headway is the time gap between consecutive pedestrians at the specified measuring location given by the following equation:

$$t = t_n - t_{n-1} \qquad \text{Equation 1}$$

Where,
t_n = time at which the lead pedestrian (n) passes the measuring location
t_{n-1} = time at which the following pedestrian (n-1) passes the measuring location
t = headway of pedestrian (n)

To further understand the performance of the corner and middle exit from the safety point of view, the headway distributions into three classes: gaps up to 0.2 s in length, gaps greater than 0.2 s up to 0.4 s, and gaps greater than 0.4 s were setup as shown in Table 2. As can be seen from the Table 2, the proportion of headways less than or equal to 0.2 s is higher in the case of the corner exit as compared to the case of the middle wall exit for normal walking. Likewise, proportion of headways is lesser for other classes as compared to middle exit. For slower running, although the proportion of headways less than or equal to 0.2 s is higher in the case of the middle exit as compared to the case of the corner exit, the proportion of headways greater than 0.2 s up to 0.4 s is higher in case of the middle exit as compared to the case of the corner exit.

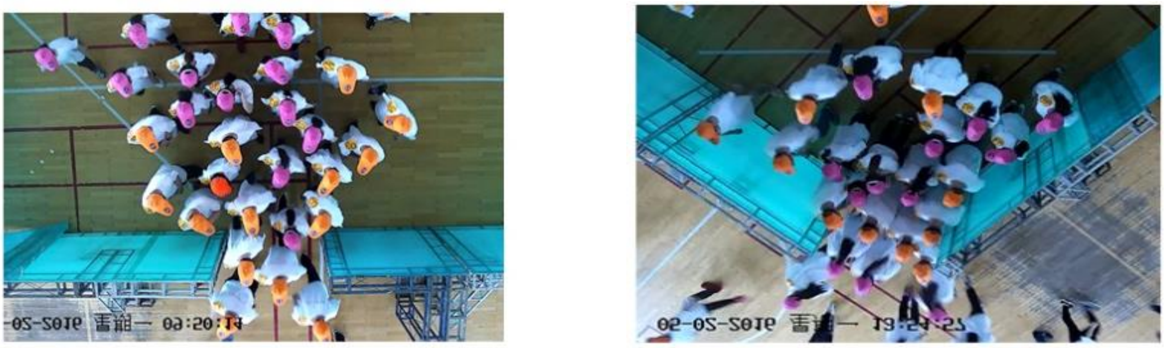
These results suggest that in overall, exit located at the corner reduces the frequency of long time headways (>0.2s) thereby facilitating the rapid succession of exits compared to when the opening is located in the middle of the wall. Long headways have been associated with clogging at bottleneck (Tajima and Nagatani, 2002; Helbing et al., 2005; Kretz 2007; Shiwakoti et al., 2014) which can result in stampede. Further, additional delays resulting from long headways are critical during emergency situation as survival in an emergency evacuation could be a matter of a few seconds.

Table 2: Frequency of headways for middle and corner exits

Frequency of headways in exit points for all repetitions				
Interval (s)	Middle exit (Normal Walking)	Corner Exit (Normal Walking)	Middle exit (Slow Running)	Corner Exit (Slow Running)
t<=0.20	39 (27%)	53 (36%)	65 (44%)	62 (42%)
0.20<t<=0.40	40 (27%)	35 (24%)	56 (38%)	59 (40%)
t>0.40	68 (46%)	59 (40%)	26 (18%)	26 (18%)

Recently the authors extended the above pilot experiments and completed full-fledged experiments on corner vs. middle exit performance with the realistic solid walls as boundary materials as shown in Figure 3 below. Although the complete statistical analysis are currently underway, it was observed that compared to middle exit, corner exit was efficient in terms of outflow by 8% (normal walking) and 24% (slow running) and were statistically significant (p value <0.05).

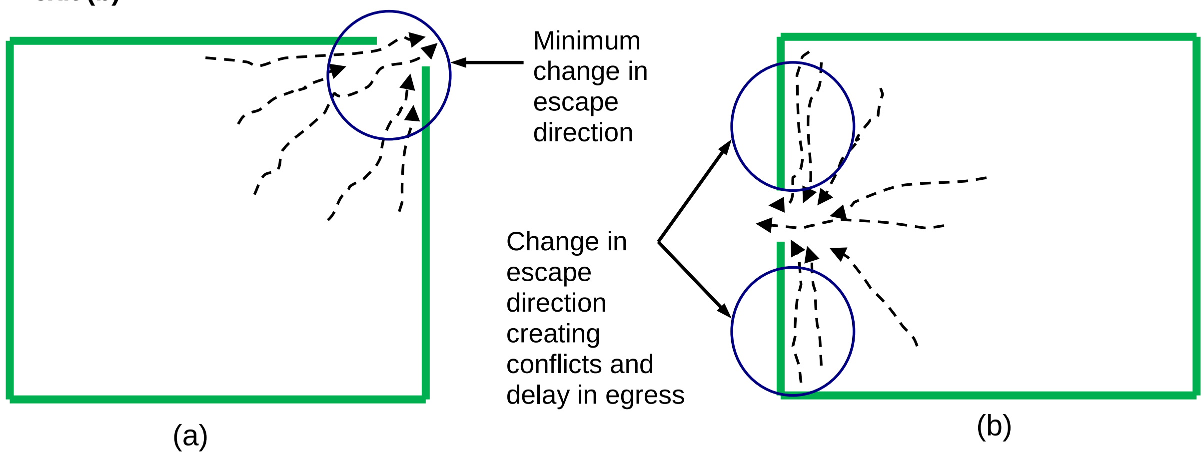
Figure 3: Recent experiments with solid walls boundary materials (a) middle exit (b) corner exit



(a) (b)

When the videos of experiments (with and without solid walls) were qualitatively examined, it was observed that the pedestrians exiting at the corner had freedom to escape without much change in their original direction. In contrast, the pedestrians exiting through the middle exit had a mix of two pedestrian streams: one that was moving straight towards the exit and the other that needed to change their directions in order to get out of the exit. This is best illustrated by Figure 4 (also refer Figure 1 c &d) where it can be seen that the movement at the corner takes a form of efficient escape channel (similar to a cone-shaped channel) facilitating the outflow (with minimum change in direction of exiting people). However, the collective movement at the middle exit is affected by the movement at the sides of the wall where change in direction of flow occurs. The previous documented crowd disasters (Chertkoff and Kushigian, 1999) and simulation studies (Shiwakoti et al., 2011b; Dias et al., 2012; Dias et al., 2013; Dias et al., 2014; Shiwakoti et al., 2014) have demonstrated that the change in escape direction can create delays and stampedes. Further, conflicts due to different directional movements are also critical from safety point of view (Shiwakoti et al., 2015; Shi et al., 2016). Hence it can be seen that corner exit is desirable as compared to middle exit from safety perspective.

Figure 4: Conceptual representation of the role of escape direction in corner exit (a) and middle exit (b)



4. Conclusion

Pedestrian crowd control and evacuation management is growing given the global trends of mass urbanization, mega-events and frequent occurrence of natural and human made disasters. As noted from the previous documented studies of crowd disasters, architectural configurations such as bottlenecks can create hazardous situations. In the past, a combination of socio-psychological and simulation models for crowd panic have provided insight into the differing decisions about the performance of architectural features of an escape area with respect to the outflow and safety of the pedestrians. One of the limitations identified was the scarcity of empirical data with human subjects that examines the design solutions to enhance the crowd safety. In this paper, the effectiveness of different exit location (corner vs. middle) to improve the escape outflow and safety of people was examined using insight from a controlled pilot laboratory egress experiments.

It was found that the corner exit was more efficient in terms of outflow of the individuals as compared to the middle exit under both normal and slow running condition. This improvement in outflow was due to less long headways in corner exit as compared to middle exit. Further, corner exit minimises the pedestrian conflicts at the egress points which is critical from safety point of view as any additional delays due to such conflicts can potentially lead to negative consequences like stampede. Also results from the recent experiments with solid boundary walls suggest that creating realistic experimental setup (as compared to walls created by chairs/desk) can influence the results to some extent. However, the generality of observation (i.e. corner exit is efficient in terms of outflow as compared to middle exit) is similar.

In future, we will conduct detailed statistical analysis of the data obtained from the recent experiments with solid walls boundary materials. Nevertheless, this paper has demonstrated that with the given layout of the escape area, there is a scope to adjust the architectural elements to optimize the maximum outflow and enhance the pedestrian crowd safety at the egress point. By making appropriate architectural adjustments within the escape area, there is the possibility of changing the collective movement patterns in a way that enhances the safety of the crowd. This can have implications towards the design of buildings in choosing the appropriate location of exits, optimising the turning angles for corridors, reducing the conflict points etc. Such empirical data would allow testing mathematical model intended to simulate emergency (panic condition) by simulating variety of scenarios at bottlenecks, identifying potential problems, their consequences, and the outcome of collective dynamics. Insight into such microscopic variations would assist in advancing understanding of what properties of emergency egress are inherent to the physical nature of the crowds, and what properties depend on the idiosyncratic details.

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