Simulation of Pedestrian Walking Through Angled-Corridors for Evacuation Behaviour Study

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Abstract. The effect of acute- and obtuse- angled-corridors on the evacuation behaviour is rarely studied. In the previous work, we have confirmed that corridor with less than 90° turning angle has negative impact to the pedestrians walking behaviour due to the tendency of the pedestrians to slow down their motion when approaching the turning of the corridor. This restrict the flow of walkers during high-density situation and cause congestion near that turning of the corridor. In this contribution, empirical data collected from previous experimental work is utilised to further study the effect of turning angle on the evacuation behaviour. The simulations of walking through angled-corridor were reproduced which reflects evacuation scenarios. Three different types of angled-corridor are taken into consideration (a 60°-, a 90°-, and a 135°- angled-corridors) with different sets of number of pedestrians (NOP: 60, 70, 80, 90 and 100). Three metrics of evacuation behaviour measurement are reported: (1) inflexion points, (2) escape time, and (3) interaction force. Inflexion point is used to evaluate the restriction flow occurred during the evacuation. From the results, the 60° angled-corridor contained the highest number of inflexion points. With the highest number of inflexion points, the escape time for the 60° angled-corridor is 14.8% to 24% longer compared to the other two types of angled-corridors. This shows that this kind of angled-corridor need to be avoided in the future design of walkways. On top of that, the 60° angled-corridor also gives the maximum interaction force with 213.75 N. This reconfirmed that the corridor with less than 90° turning angle is not suitable to be built as a walkway. This work is relevant to be studied due to its immediate applications in assessment of crowd safety for building egress.

1. Introduction

Many complex geometries of walkways can be witnessed in public buildings (like train stations, shopping malls, universities and parks) and one of their kinds is an angled-corridor. In our previous experimental study on pedestrians walking through angled-corridor [1], we have confirmed that corridor with less than 90° turning angle (i.e. 60° angled-corridor) has negative impact to the pedestrians walking behaviour due to the tendency of the pedestrians to slow down their motion when approaching the turning of the corridor. This could restrict the flow of walkers during high-density situation and cause congestion near that turning angle of corridor. As the turning angle of corridor increases (i.e. 135° angled-corridor), the impacts to pedestrian walking velocity become less.
The findings in the previous study is crucial to be further studied in postulating the effect of angled-corridor on evacuation behaviour. From current literature review conducted, the effects of acute and obtuse angled-corridors on evacuation behaviour is still limited. Shiwickoti et al. (2011) [2] highlighted the importance aspect of collective egress under emergency conditions is the turning movement when a sudden change in the direction or the layout of the escape area occurs. Dias et al. (2012) [3] suggested that right angles in the egress path are 20% to 25% less effective compared with the straight egress paths. As further examination with microsimulation suggests, this figure could be as significant as 65% for higher densities.

In this contribution, empirical data collected from previous experimental work [1] is utilised to further study the effect of turning angle on the evacuation behaviour. The simulations of walking through angled-corridor were performed which reflects evacuation scenarios. Three different types of angled-corridor are taken into consideration (a 60°, a 90°, and a 135° angled-corridors) and three metrics of evacuation behaviour measurement are reported. This work is relevant to be studied due to its immediate applications in assessment of crowd safety for building egress.

2. Methods
This study is the continuation of the previous study [1]. In the previous study, we reported experimental findings of pedestrians walking behavior while walking through angled-corridors. The setting of the angled-corridor is as shown in Figure 1. From that study, we came to the conclusion that pedestrians tend to slow down their walking pace when approaching the turning angle of the corridor (β). In high density situation, restriction to the flow of walkers could be triggered. Hence, these findings are worth to be further studied in postulating the effect of turning angle on evacuation behavior.

![Figure 1. Schematic of angled-corridor.](image)

To facilitate this study, a microscopic Distinct Element Method (DEM)-based model, which has been used previously in simulating hypothetical evacuation scenarios [4–6] is employed. DEM-based model is capable to calculate the interaction force (between humans and boundaries) and egress time, in which the important metrics of evacuation behavior measurement in this study.

2.1. Validation of the model
For determination of the degree of validity of the model, pedestrians walking through angled-corridor was reproduced first by using DEM-based model. This validation work is crucial to confirm the reliability of DEM-based model. From the previous experimental work, three walking scenarios were selected to be reproduced: a 60° angled corridors with number of persons (NOP) 60, a 90° angled-corridors with NOP 60 and a 135° angled-corridors with NOP 60. The reliability of the model is based...
on the comparison of ‘time-in’ and ‘time-out’ near turning angle of corridor between simulation and empirical data from [1]. If the difference between simulation and empirical data is less than 5%, the model is considered reliable.

2.2. Simulation of evacuation scenarios
In studying the turning angle effect on evacuation behaviour, simulations were performed for three different angled-corridors: a 60°-, a 90°-, and a 135°- angled-corridors and five different number of pedestrians (NOP) were simulated: NOP: 60, 70, 80, 90, and 100. Note that the NOP is the variable used in this simulation works. It starts with NOP 60 and increase by 10 until achieve NOP 100. The NOP starts from 60 because of the maximum participation in the previous experimental work is up to 60 pedestrians. A total of 15 simulations is conducted. Three metrics of evacuation behavior are collected from these simulations: (1) inflexion points, (2) escape time, and (3) interaction force.

2.3. Safe level of interaction force
The interaction force acting on each pedestrian is a significant output from the current simulations. This metric can be used to confirm the interaction between pedestrians are in the safe level. Previously, the investigations of injury on human have been reported. The experimental works on the maximum endurable force during earthquake evacuation had been conducted by [7]. They found that the maximum endurable contact force that can be withstood by a fit young female and a middle aged male weighing 60 kg and 74 kg is 162 N minimum and 242 N maximum. Meanwhile, study conducted by [8] on the level of comfortable loads for twenty-one pedestrians with the range of age 20 to 25 years old had been tested on three barrier types loaded on upper and lower chest and abdomen. They found that the comfortable limit of loads was ranged from 175 N to 247 N. Hence, the benchmark for the safe level of interaction forces used in this study is in the range of 162 N and 242 N as discovered from the most recent studies [7].

3. Results and discussion
The results are discussed according to the following criteria: (1) reliability of DEM-based model; (2) restriction flow due congested situation; and (3) the safe evacuation.

3.1. Reliability of DEM-based model
During the experimental work [1], the ‘time-in’ and ‘time-out’ near the turning angle of corridor has been collected. The ‘time-in’ is measured when the first pedestrian reached the red line (1 m before the turning angle) and the ‘time-out’ is measured when the last pedestrian reach the yellow line (1 m after the turning angle) (shown in Figure 2). Similarly, in the simulation works, the ‘time-in’ and ‘time-out’ of the pedestrians are also collected. Then, the comparison is made between findings in [1] and simulation works.

| Task | Angled-corridor | Experiment | Simulation |
|------|-----------------|------------|------------|
| 37A  | (NOP 60) 60°    | Time in: 3.14 s | Time in: 4.00 s |
### 37A (NOP 60) 60°
- Time out: 47.04 s

### 13B (NOP 60) 90°
- Time in: 4.18 s
- Time out: 45.00 s

### 29B (NOP 60) 135°
- Time in: 4.13 s
- Time in: 5.00 s
Figure 2. The time-in and time-out for experimental and simulation works.

From Table 1, it shows that the difference of 'time-in' and 'time-out' at angled-corridors between experiment and simulation works are acceptable. The percentage range of the differences are between 0.48% to 2.51% and the time differences between experimental and simulation are ranged around 0.06 s to 1.10 s. Hence, the DEM-based model is considered reliable and suitable for this study. Meanwhile, Figure 2 shows visually the ‘time-in’ and ‘time-out’ for both experimental and simulation works.

Table 1. Difference of time-in and time-out at angled-corridor between experiment and simulation works.

| Angled-corridor | Experiment | Simulation | (A) – (B) | %  |
|-----------------|------------|------------|-----------|----|
|                 | Time-in (s)| Time-out (s) | Difference (s)| Time-in (s)| Time-out (s) | Difference (s)|       |
| 60°             | 3.14       | 47.04      | 43.90     | 4.00       | 49.00       | 45.00       | 1.10   | 2.51 |
| 90°             | 4.18       | 44.12      | 39.94     | 5.00       | 45.00       | 40.00       | 0.06   | 0.15 |
| 135°            | 4.13       | 37.29      | 33.16     | 5.00       | 38.00       | 33.00       | -0.16  | -0.48|

*Can be referred in [1]

3.2. Restriction flow due to congested situation

In measuring the restriction flow that may occur at the turning angle of the corridor, the time taken to complete the task of walking through angled-corridor (escape time) is plotted versus the number of escaped pedestrian (NEP). Figure 3(a)–(e) show the graph of the escape time versus NEP for different number of pedestrian (NOP). From the graphs, it can be witnessed that, the 60° angled-corridor takes longer time than the other two types of angled-corridor.

Table 2. Number of inflexion point counted.

| Angled-corridor | NOP 60 (SIM1-SIM3) | NOP 70 (SIM4-SIM6) | NOP 80 (SIM7-SIM9) | NOP 90 (SIM10-SIM12) | NOP 100 (SIM13-SIM15) |
|-----------------|---------------------|--------------------|--------------------|----------------------|-----------------------|
| 60°             | 10                  | 11                 | 12                 | 9                    | 5                     |
| 90°             | 10                  | 8                  | 7                  | 9                    | 5                     |
| 135°            | 4                   | 6                  | 5                  | 7                    | 5                     |
To confirm further the reason of longer time taken in 60° angled-corridor, the inflexion points are observed and counted (as shown in circle in Figure 3). The inflexion points are the uniform lines in the graphs. These inflexion points indicate that the flow is restricted at certain points along the corridor. Table 2 shows the frequency of the occurrence of the inflexions points for every type of angled-corridor. The highest inflexion points is observed at 60° angled-corridor. This confirmed that the restrictions of flow mostly occurred at 60° angled-corridor.

**Figure 3.** The escape time versus the number of escaped pedestrian (NEP) for all types of angled-corridor (from NOP 60 to 100).
Figure 3. (continue) The escape time versus the number of escaped pedestrian (NEP) for all types of angled-corridor (from NOP 60 to 100).
3.3. The safe evacuation

As mentioned earlier, the interaction force acting on each pedestrian is a significant output from the current simulations. This force can be used to affirm the safest evacuation scenario simulated so that the findings from this study are more valuable.

A time series of maximum interaction force is plotted (Figure 4). The interaction force analysis was conducted to ensure the maximum interaction force acting on each pedestrian is within the safe level of interaction force (162 N – 242 N). Meanwhile, Table 3 shows the maximum interaction force with the snapshots for NOP 80 for all three types of angled-corridor. The snapshots visualise the situation at time the maximum interaction force occurred for each types of angled-corridor. As can be seen, during t = 38 s, at 60° angled-corridor, the pedestrians accumulate near the turning angle of corridor. This shows that a 60° angled-corridor has a strong tendency for a congestion to occur. Similar situation occurs at the 90° angled-corridor at t = 32 s. Meanwhile, in 135° angled-corridor, less pedestrians are seen accumulated near the turning angle. This confirmed our previous findings which pedestrians prefer to occupy space available to suit their own speed and comfort since the corridor is nearly similar to the straight corridor.

![Figure 4. The time series of the maximum interaction force.](image-url)
Figure 4. The time series of the maximum interaction force.
Table 3. Maximum interaction force for Inter-3 with NOP 80.

| Number of pedestrian | Angled-corridor | Max. inter-element force (N) | Snapshot from simulation work |
|----------------------|----------------|-----------------------------|------------------------------|
| Inter-3 (NOP 80)    | 60°            | 213.75                      | t = 38 s                     |
|                     | 90°            | 126.98                      | t = 32 s                     |
|                     | 135°           | 91.29                       | t = 26 s                     |

4. Conclusion
In this contribution, the simulation works are performed to further study the effect of angled-corridor on evacuation behaviour. Three metric of measurements were collected: (1) inflexion points, (2) escape time, and (3) interaction force. Inflexion point is used to evaluate the restriction flow that may occur during the evacuation. As can be witnessed, the 60° angled-corridor contained the highest number of inflexion points. With the highest number of inflexion points, the escape time for the 60° angled-corridor is longer. This shows that this kind of angled-corridor need to be avoided in the future design of walkways. On top of that, the same corridor also gives the maximum interaction force with 213.75 N. This reconfirmed that the corridor with less than 90° turning angle is not suitable from the perspective of safety issue.
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