Expected evacuation distance affects the evacuation efficiency of crowds in super high-rise buildings: an empirical analysis

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Abstract This study focuses on the evacuation characteristics of pedestrians in super high-rise buildings. Three experiments are conducted, including evacuation drills in two iconic super high-rise buildings: Shanghai Tower and Jinmao Tower, as well as evacuation experiments with different expected evacuation distances on an evacuation test platform for simulating super high-rise buildings. The findings indicate that the expected evacuation distance exerts significant influence on the desired speed of pedestrians during long-distance stairwell evacuation. Pedestrians with longer expected evacuation distances who depart from higher floors prefer to evacuate with relatively lower speeds at the early stage of the evacuation to conserve physical strength for the whole procedure. Conversely, as they get closer to the safety area, the expected evacuation distance gradually decreases and speed-up behavior enabling rapid completion of final evacuation stages are observed.

Keywords Super high-rise buildings; Expected evacuation distance; Experiment; Evacuation speed

Experiments

Continuous downward movement through stairwells can easily lead to physical exhaustion or reduced speed among evacuees, while complex group behaviors further affect evacuation efficiency. The complexity of speed variations during ultra-long distance stairs evacuation inadequately explored. The acquisition of empirical data on super high-rise evacuation dynamics remains constrained by architectural complexities and pedestrian safety, making it challenging to conduct analysis of localized evacuation behavior. Hence, three sequential super high-rise building evacuation experiments were systematically conducted, focusing on the speeds variation of pedestrians facing long-distance stairs evacuation.

Experiment A was conducted in the Shanghai Center Tower, which is the tallest building in China with a height of 632m and 126 floors above ground. 69 participants whose ages ranged from 20 to 51 years old were divided into two groups: Group 1 (41 participants) initiated evacuation from the 126th floor, while Group 2 (28 participants) commenced evacuation from the 117th floor when the participants of Group 1 reach. The experiments ended when all the participants reach the ground floor. Localized evacuation characteristics were extracted and analyzed using surveillance video data of each floor from the stairwells of the Shanghai Tower, with the exception of a few floors without surveillance cameras.

Experiment B was conducted on an evacuation test platform for simulating super high-rise buildings based on a 12-story building. Panoramic camera equipment installed on all levels. Participants moved from the 12th floor to the 1st floor and then took the elevator back to the 12th floor, which was defined as one lap. They were asked to repeat multiple laps to simulate the evacuation distance of super high-rise buildings. Different expected evacuation distances were achieved by asking participants to run 9, 10, and 11 laps (11 laps is the 132nd floor, others are similar). A total of 24 participants were recruited for the experiment, with a male to female ratio of 1:1, and were evenly divided into 4 experimental groups. Each participant was tested individually in sequence.

Experiment C was conducted at the Shanghai Jinmao Tower, a 420m tall skyscraper with 88 stories. Surveillance cameras were deployed at 4-floor intervals within stairwells to capture evacuation dynamics. 60 participants were allocated into four groups (14-16-14-16 configuration) and dispatched to initiate evacuation from the 87th, 75th, 63rd, and 51st floors respectively. The evacuation sequence was as follows: Evacuee on the 87th floor first evacuate, then once any evacuee reached the platform on the 75th floor, evacuee on the

75th floor could commence, and so on.

Conclusions

The results of experiment A showed in Figure 1(a) demonstrated two stages of speed variation. In the first stage, the merge of pedestrians led to a high density within the space, causing a decline in crowd speed; in the second stage, as pedestrians gradually dispersed and spatial density decreased, the speed gradually increased and returned to the free speed. Meanwhile, under the influence of expected evacuation distances, Group 1 exhibited a significantly lower average evacuation speed of 0.730 ± 0.213 m/s compared to Group 2 (0.767 ± 0.217 m/s). The phenomenon revealed that pedestrians, influenced by spatial density and the longer evacuation distances, tend to choose lower evacuation speeds to cope with the increased physical exertion and psychological pressure. Based on experiment A, we argued that, during long-distance stairwell evacuations, the expected evacuation distance significantly affects the desired speed of evacuees due to body energy limitations.

The experiment B was conducted to validate this hypothesis. The experimental results (Figure 1(b)) showed that pedestrian speed exhibit a decreasing trend with increasing evacuation distance. The longer the expected evacuation distance, the smaller the average evacuation speed of pedestrians. Furthermore, a phenomenon on the speed fluctuation was also observed: once or twice speed boosts were prone to occur when the expected evacuation distance decreased, especially when pedestrians were close to the target node. This non-linear pattern of speed variation revealed that evacuees in long-distance stairwell evacuations adopt a speed reduction strategy to save on physical exertion based on the judgement of the expected evacuation distance, and will have a speed-up behavior when approaching the target node (with a shorter expected evacuation distance). The findings validate that evacuees' speed selection is significantly governed by expected evacuation distances during super high-rise building evacuations.

Finally, the experiment C results verified that the average evacuation speed for higher departure floors (those with longer expected evacuation distances) was smaller than those for lower departure floors, as shown in Figure 1 (c). Figure 1(d) gave the expected evacuation distance governs pedestrians speed selection in super high-rise evacuations. A significant convergence in crowd speed distribution was observed as evacuation distance increases. The experiments further confirmed the impact of expected evacuation distance on crowd evacuation speed.

Through a series of experiments, we have drawn the following conclusions: expected evacuation distance affects pedestrian evacuation speed, with longer expected distances prompting individuals to adopt speed reduction strategies to rationally allocate body energy. Simultaneously, pedestrians' speed increases after taking a rest. Additionally, the confluence phenomenon in stairwells significantly reduces overall evacuation efficiency. These findings emphasize the need to integrate distance-dependent speed modulation into evacuation strategies for improved emergency management. It is crucial to optimize existing norms and emergency management strategies based on more detailed crowd-movement data.

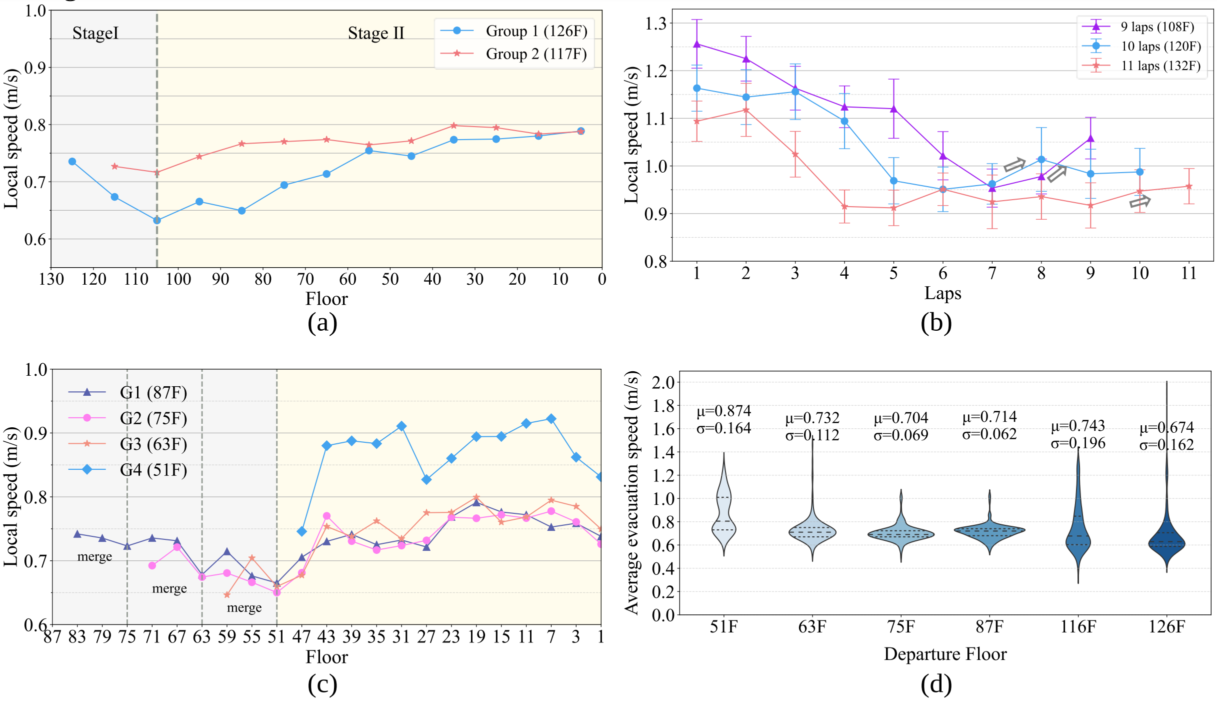

Figure1: Local speed results for different experiments. (a) Variation of local speed with floor for two experimental groups in experiment A. (b) Variation of local speed in different experimental groups in experiment B. (c) Variation of local speed with floor for different experimental groups in experiment C. (d) Evacuation speed data for the first 48 floors of each experimental group in experiments A and C.

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