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Article

Study on Group Movement Characteristics in Stairwell of High-Rise Buildings

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Abstract: In order to cope with limited land availability and the increasing urban population, more high-rise buildings are being built throughout cities, but this has also led to new challenges in the emergency evacuation of people. Therefore, we conducted an evacuation experiment of a group of people in the stairwells of high-rise buildings to explore the movement law of groups in stairwells. The experiment had 18 scenes, including the evacuation movement of an independent group and the crowd evacuation movement of different groups. Analyzing the independent groups' movement showed that regardless of the type of group, the average speed of the crowd was more than 1.2 m/s, which was longer than that of previous studies. The more constraints in the evacuation process, the smaller the speed difference between males and females. Group cohesion was mostly concentrated at about 1 s. Moreover, group velocity and cohesion were found to have no significant correlation in stairwell movement. Analyzing the crowd evacuation time of eight different scenes showed that it took longer for crowds bearing weight to evacuate than those not bearing weight. According to the spatiotemporal evolution of crowd evacuation in stairwells, the crowd moves intermittently in the evacuation process, especially in the early and middle stages of evacuation, and the influence of group factors on this process was not obvious. Regardless of the kind of scene or stairwell, the number of pedestrians generally first increased and then decreased to a significantly low value, and the number of pedestrians reached about 30 in the scenario of people without any load. Additionally, the speed of the pedestrians entering the stairwell in the back of the group was not faster than that of the pedestrians in the front, which showed that pedestrians rarely engaged in overtaking behavior. The research results of this paper not only enrich evacuation research but also provide support for the design of high-rise stairs.

Keywords: high-rise building; group movement; crowd evacuation; group cohesion

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1. Introduction

At present, there are over 347,000 high-rise buildings in China, making it the country with the largest number of high-rise buildings in the world. With so many high-rise buildings, the incidence of high-rise fires is increasing, and the death rate of high-rise building fires accounts for more than 80% of total fire deaths. The special design, complex functions, dense crowds, and many fire hazards of high-rise buildings have led to significant pressure for high-rise fire prevention [1]. The "615" fire in London and the Torch Building fire in Dubai have forced us to face up to the fire hazards of high-rise buildings, and the emergency evacuation of people in the fire environment of high-rise buildings has become a research hot spot.

The staircase is the key part of a building's evacuation system. Studying the pedestrian evacuation rules in stairwells can aid knowledge of the evacuation process of high-rise buildings. Because of the special structure of stairs, pedestrians' movement in stairs is more difficult than that in horizontal ground passages, and the width, height, depth, intermediate landings, and handrail position of stairs [2,3] all have an impacts on the movement of pedestrians. When pedestrians enter a stairwell from a corridor, their movement characteristics change. Furthermore, due to the confluence of different pedestrian flows in a platform [4–6], the stair area of a building can become a bottleneck in the evacuation process. In the process of building evacuation, pedestrians' gender [7], age [8,9], environmental familiarity, body size [10], and other attributes also affect their movement characteristics (such as speed, density, and flow rate), which have far-reaching effects on both local evacuation and overall evacuation. In addition, environmental factors such as lighting [11] and the setting of the evacuation system [12] also affect the evacuation process in stairwells.

Therefore, many scholars have studied the law of crowd movement in stairwells. As a key parameter of pedestrian dynamics, speed is the most widely studied by researchers. Pauls et al. [13] observed a pedestrian speed of between 0.61 m/s and 0.81 m/s. Fang et al. [14] carried out high-rise evacuation experiments to study the movement characteristics of people in the evacuation process of building stairwells; they found that pedestrian speed had an approximately normal distribution and that the average pedestrian speed during the entire experiment was 0.81 ± 0.13 m/s. Choi et al. [7] found that the average speed of men and women going downstairs was 0.83 m/s and 0.74 m/s, respectively, and the average speed of men and women going upstairs was 0.66 m/s and 0.48 m/s, respectively. Yang et al. [15] observed the movement of pedestrians going downstairs during after-school students and evacuation exercises, and they found that the speed of pedestrians under emergency conditions was faster than that under normal conditions and that subgroup phenomena existed. Generally, two or three people formed a subgroup. The speed of such a group was smaller than that of a single pedestrian, and the group also affected the speed of others. Compared with that in plane movement, individual pedestrian speed in stair movement was found to be more likely to affect overall speed.

As research deepened, people gradually began to pay attention to the evacuation characteristics of vulnerable crowds in building stairwells. Larusdottir et al. [8] conducted several evacuation experiments in four childcare centers to study children's movement characteristics. They deemed that familiarity with the surrounding environment affected children's evacuation efficiency, and the more familiar children were with stairs, the faster they could evacuate. At the same time, it was found that children's exit evacuation flow rate was higher than that of adults, which may be caused by children's smaller size. Kuligowski et al. [16] studied the evacuation process of the elderly or disabled people with and without help (self-evacuation, crutch assistance, assistance from another resident or fireman, or assistance from others), and they obtained the average crowd velocity and average individual velocity. In order to obtain a reference value of evacuation speed under load conditions, Liu et al. [17] carried out individual and group evacuation experiments under different load conditions in stairwells, obtaining the evacuation speed and evacuation time laws of people with different physical indicators, and they studied the influence of evacuation floors on evacuation speed. Fujiyama et al. [18] studied the influence of pedestrian obesity and stair slope on pedestrian stair movement in great detail, and their results showed that stair slope had an effect on pedestrian stair movement speed but obesity had no effect on pedestrian stair movement speed, which was consistent with Choi's research [7]. Koo [19] proposed a phased evacuation strategy that applied a fixed evacuation delay to residents with wheelchairs in a high-rise building to reduce aggregated evacuation times, but delaying the evacuations of specific groups of individuals might not be ethical or accepted. Delin et al. [20] carried out two experiments on people's behavior when climbing stairs with heights of 48 and 109 m, and they studied the effects of physical consumption on walking speed, physiological performance, and behavior during evacuation. Their results showed that physical work ability affected walking speed in the case of long-term evacuation.

At the same time, the characteristics of known buildings and unknown buildings, such as building structure, the setting of the evacuation system, visibility of the staircase [21] and other environmental factors, also affect the evacuation process. Campbell et al. [5] studied occupant merging behavior on stairwell landings, and they found that the transit ratio, which is the normal transit time of the stairwell landing divided by the merging transit time, was 0.67 and 0.70 for the floor and stair flows, respectively. Sano et al. [4] studied the relationship between the density and speed of evacuees on the landings for two situations: without and with merging in the stair flow in a crowded high-rise building. It was observed that when the staircase was fully crowded, the density on the landings in a moving situation was different from that in a stopped situation. Moreover, the density on the landings was different from that on the treads. Enricoronchi et al. [22] used a probability method to analyze 215 pedestrians' movement tracks and studied the influence of congestion and pedestrian interaction on evacuation path probability. Their results showed that the more pedestrians there were, the longer the pedestrian movement path was and the greater the utilization rate of the stairs. Kodur et al. [23] examined occupant evacuation scenarios in fire-exposed high-rise buildings and then conducted a parametric study on evacuation strategies. The results from the study indicated that the two most significant factors that influenced evacuation time were the location of stairways within building and the floor at which a fire starts. When a fire started at the lower level of a building, the evacuation time was the highest. Soltanzadeh et al. [24] considered 12 different scenarios to investigate the optimal time of emergency egress in a 40-story high-rise office building. The results of the research showed that having a refuge floor in the middle of the building allowed more people to be evacuated; this could be a feasible strategy, in that making less nodes in a refuge floor plan could prevent the formation of long queues for the use of elevators. Hagwood et al. [25] used the self-exciting Hawkes point process as a means to capture occupant interactions in stair exit processes, and they used this point process representation to derive a minimum stair width determination that compensated for human interaction. Finally, they derived a point estimate of 1.308 m for minimum stair width and a 95% confidence interval of (1.193 m, 1.334 m) for bounding minimum stair width.

Ding et al. [26] studied the effects of non-irritant smoke and participants' knowledge on evacuation procedures (especially elevator evacuation). The evacuation times for the elevator versus stairs, the proportion of elevator users, elevator wait times, and redirect behaviors were analyzed and discussed. Wright et al. [27] conducted an evacuation drill experiment in an office building and studied the evacuation process of people passing through a smoke-filled interlayer under different lighting conditions (normal lighting conditions, emergency lighting environment, electric laser guidance system, incandescent lamp and diode lamp). Zeng et al. [28] conducted experiments on the individual free movement of pedestrians under different illumination conditions in high-rise building. Participants in the experiments simulated environments with 100%, 12% and 0% illumination by wearing glasses with different transmittance levels. The results showed that the illuminance in stairwells and the use of handrails affected the pedestrians' movement tendency and speed. Through the research of an unannounced evacuation experiment performed on the 16th floor of a 35-floor high-rise hotel building, Mossberg et al. [12] found that people typically chose the elevator for evacuation, even if their hotel room was located closer to evacuation stairs. Flashing green lights next to an evacuation sign made people look more at this sign. However, the flashing light was not shown to significantly improve compliance with the sign. After summarizing the research status of high-rise building evacuation, Ding et al. [29] concluded that future research should focus on quantitative pre-evacuation behavior, the elevator's assistant function, and the impact of group relations on evacuation.

In addition to the structure of the stairwell and the characteristics of personnel movement, the fire safety facilities of the stairwell, such as the fire alarm system, smoke control and the exhaust system, will also affect the evacuation process. The smoke control and the exhaust system mainly provide protection for the fire evacuees and firefighters who put out the fire. The automatic fire alarm system can detect the early characteristics of the fire, send out the fire alarm signal, and provide control and instruction for the evacuation of personnel. Chiangaek et al. [30] researched safety analysis of a hospital building and found that a non-operative fire alarm system greatly increased evacuation time. At the same time, the fire escape door became an evacuation bottleneck, which needed to be widened. Sekizawa et al. [31] carried out an analysis of reports of cases where residential fire alarms successfully worked, and indicated the potential for persons in the room of fire origin at the time of the fire to be saved by others nearby because of the activation of residential fire alarms, even if they are sleeping and do not respond by themselves to the alarm sound. Cai et al. [32] proposed a fire-safe elevator system and numerically studied the fire hazards associated with this design in an example building. The results showed that the smoke extraction system could only delay smoke spread to the elevator shaft near the fire source for a short time. A pressurization system could confine the smoke to the floor with the area of fire for a sufficiently long time period for safe evacuation. For safety reasons, the building's users should improve the door size and install a smoke barrier on both sides of the stairs at all floors to increase the evacuation ability [33].

The social attributes of human beings make them work in groups, not as isolated individuals, when participating in various activities. In the evacuation process, the influence of the social relationships between people on the evacuation process should be considered. In this study, we carried out a series of pedestrian group movement experiments, with 18 types of evacuation scenarios, and detailed information about the experiment can be seen in Section 2. Through the analysis of our controllable experiment, we hoped to examine more group movement behaviors in stairwells and provide support for the establishment of group motion models.

2. Experimental Setup

This experiment was carried out in the stairwell of an 18-story high-rise residential building, and the structure and size of the building stairs are shown in Figure 1. W1, W2, W3, W4, W5, and W6 were found to be 1.72 m, 1.17 m, 1.05 m, 2.34 m, 0.27 m, and 0.16 m, respectively, and each staircase contained 8 treads not including the platform area. The gray fan-shaped area is the shooting range of the cameras, and the red line is the marking position for pedestrians to reach a certain floor.

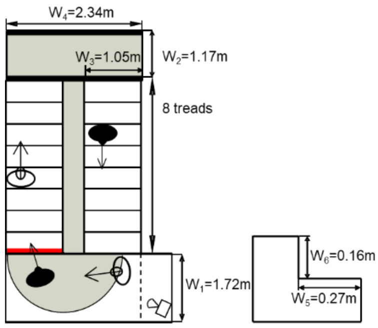

Figure 1. Structural dimensions of stairs.

All participants were adult college students. The students volunteered to take part in the evacuation experiment and had a certain understanding of the content and purpose of the experiment. Two types of evacuation experiments were carried out: single group movement experiments and crowd with groups evacuation experiments. The former mainly considered the micromovement characteristics of different types of groups in the stairwell, while the latter mainly considered the macromovement characteristics of different types of groups in the stairwell. There were 18 evacuation scenarios in this experiment, and the specific scenario descriptions are shown in Table 1. In order to ensure the comparability of the experimental results, 18 evacuation scenarios were completed by the same group of experimental pedestrians. In order to ease the examination of experimental results, people were required to wear hats of different colors during the experiment and the same groups of people wore hats of the same colors. Before the experiment, all the people were distributed in the corridor on the 18th floor. When they heard the command, they entered the stairwell to complete the evacuation process. The evacuation process was recorded by cameras on the 17th, 15th, 13th, 11th, 9th, 7th, 5th and 3rd floors. The reason why data collection was not carried out on the first floor was that the staircases from the third floor to the first floor are smooth floors and the other floors are cement floors. According to the limitations of pedestrian movement ability, the experiment involved three kinds of pedestrians: a pedestrian who does not have any weight (called pedestrian I), a pedestrian bearing a 4 kg weight (called pedestrian II), and a pedestrian bearing 2.5 kg sandbags on his/her legs (called pedestrian III). Numbers I, II and III only represent the pedestrian category and have no other significance. Pedestrian II and pedestrian III were used to simulate the evacuation scene of a crowd under conditions of load and limited mobility. In the following result analysis, the scene numbers are consistent with those in Table 1. A screenshot of the evacuation experiment is shown in Figure 2.

Table 1. Specific description of different experimental scenarios.

Scene Number	Description	Scene Number	Description
A	Individual (1 pedestrian I)	J	A crowd with four-person groups (60 pedestrian I)
B	Individual (1 pedestrian II)	K	A crowd with individuals (30 pedestrian I, 15 pedestrian II and 15 pedestrian III)
C	Individual (1 pedestrian III)	L	A crowd with the dyads (30 pedestrian I, 15 pedestrian II and 15 pedestrian III)
D	Dyad (2 pedestrian I)	M	A crowd with the triads (30 pedestrian I, 15 pedestrian II and 15 pedestrian III)
E	Triad (3 pedestrian I)	N	A crowd with the 4-person groups (30 pedestrian I, 15 pedestrian II, and 15 pedestrian III)
F	Four-person group (4 pedestrian I)	O	Dyad (1 pedestrian I and 1 pedestrian III)
G	A crowd with individuals (60 pedestrian I)	P	Dyad (1 pedestrian A and 1 pedestrian II)
H	A crowd with the dyads (60 pedestrian I)	Q	Triad (1 pedestrian I, 1 pedestrian II and 1 pedestrian III)
I	A crowd with the triads (60 pedestrian I)	S	4-person group (2 pedestrian I, 1 pedestrian II and 1 pedestrian III)

Figure 2. The screenshot of group.

3. Results and Analysis

We used the video files captured by the cameras to extract the movement data of people on different floors, mainly the time of people passing through floors. As shown in Figure 2, the time of a pedestrian leaving the corresponding floor was obtained with manual recording.

3.1. Group Velocity

Speed is an important parameter used to characterize the movement ability of people, and its value is affected by many factors, such as building structure, lighting, and pedestrian attributes. Here, we mainly focused on the influence of pedestrian group movement mode on the speed of people. The velocities of individual pedestrians and groups were calculated with Equation (1).

$$\mathrm{v}_n = \frac{S_{n,n-2}}{t_{n-2} - t_n} \tag{1}$$

where V_n and t_n are pedestrian' velocity in the n-th floor, measured in meters per second, and the time when the pedestrian reached the n-th floor, measured in seconds, and $S_{n,\,n-2}$ is the distance between the n-th floor and $(n-2)$-th floor, measured in meters. $S_{n,\,n-2}$ contains two parts: the moving distance of the pedestrian on the step (S_n) and the moving distance of the pedestrian on the plane (S_{n-2}). The former is estimated with the length of the slope, and the latter is calculated with Equation (2). In the case of a low pedestrian density, it is assumed that the pedestrian moves along the arc on the plane. Of course, there are inevitable errors here. In future research, more detailed measurement methods are needed.

$$S_2 = \pi \times \frac{w_3}{2} \tag{2}$$

As shown in Figure 3, the average speed of pedestrians in group A, group B, group C, group D, group E, group F, group O, group P, group Q, and group S was 1.49 m/s, 1.32 m/s, 1.31 m/s, 1.30 m/s, 1.32 m/s, 1.18 m/s, 1.34 m/s, 1.19 m/s, 1.30 m/s, and 1.24 m/s, respectively. The standard deviations of pedestrian speed in group A, group B, group C, group D, group E, group F, group O, group P, and group Q were 0.26 m/s, 0.25 m/s, 0.27 m/s, 0.24 m/s, 0.2 m/s, 0.16 m/s, 0.17 m/s, 0.14 m/s, 0.18 m/s, and 0.13 m/s, respectively. Compared with individual movement, the speed fluctuation of group movement was smaller. The speed of 93% of pedestrians exceeded 1 m/s, and regardless of the type of group, the average speed of the crowd was more than 1.2 m/s. The speed of pedestrians was significantly higher than that of previous studies [34]. It is probable that most of the experimental pedestrians evacuated with the help of stair handrails and that some male volunteers even jumped multi-level stairs, which accelerated the evacuation process. Comparing the data of group A, group B, and group C, we found that the movement speed of a single individual under the condition of weight bearing is was than that of an individual walking normally. Based on the speed of group A, group D, group E, and group F, it seems that the speed of pedestrian group movement was lower than that of single individuals, which is consist with the work of [35]. However, the speed of the triads was higher than that of the dyads, which was slightly different from previous studies [36,37]. Comparing the data of group O, group P, group Q, and group S, we found that the movement speed of the dyads holding heavy objects was the lowest. In addition, a comparison of weight-bearing and non-weight-bearing people (from group D to group S) showed that weight bearing did not have a negative impact on all situations.

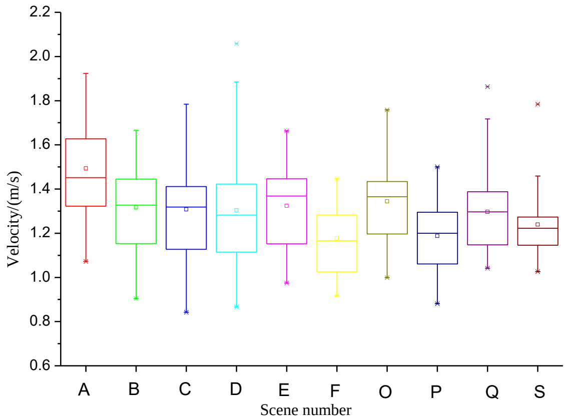

Figure 3. The movement speed of different types of groups. The scene numbers are consistent with those in Table 1.

Figure 4 shows the speed of male and female pedestrians in different scenes. The average speeds of the six groups in Figure 4a were as follows: 1.59 m/s, 1.30 m/s, 1.41 m/s, 1.131 m/s, 1.408 m/s, and 1.13 m/s. Similarly, the average speeds of the six groups in Figure 4b were as follows: 1.47 m/s, 1.22 m/s, 1.44 m/s, 1.17 m/s, 1.24 m/s, and 1.22 m/s. The average speeds of the eight groups in Figure 4c were as follows: 1.44 m/s, 1.28 m/s, 1.22 m/s, 1.19 m/s, 1.33 m/s, 1.31 m/s, 1.303 m/s, and 1.306 m/s. For most cases, the speed of men was significantly higher than that of women. There was a significant difference in speed between the men and women shown in Figure 4a,b, while there was no significant difference between those shown in Figure 4c. The difference of the evacuation scenarios in Figure 4a was related to whether pedestrians were loaded with weight, the difference of the evacuation scenarios in Figure 4b was related to the size of the group, and the difference of the evacuation scenarios Figure 4c was related to both factors. The more constraints in the evacuation process, the smaller the speed difference between males and females.

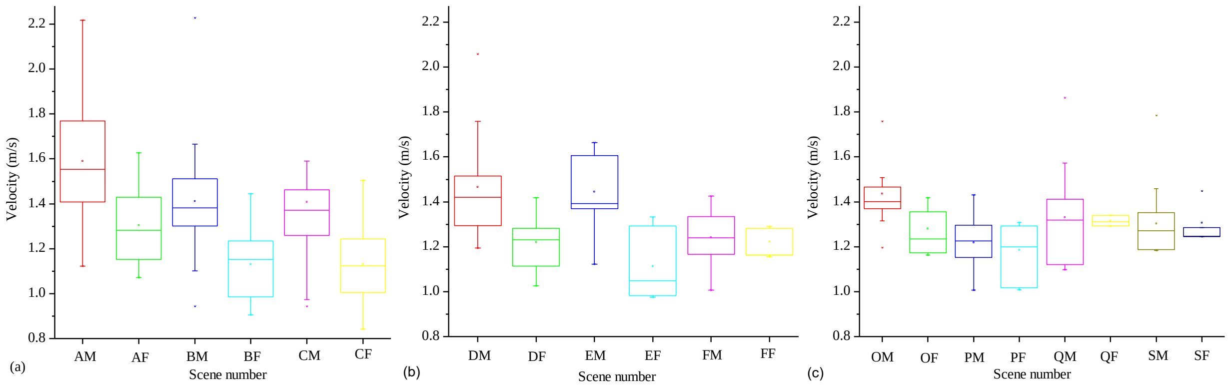

Figure 4. The effect of gender on pedestrian velocity. The first letter in the scene number represents the evacuation scene (the scene numbers are consistent with those in Table 1), and the second letter represents the gender (M and F are short for male and female, respectively). (**a**) shows male speed versus female speed in a single pedestrian movement. (**b**) represents male speed versus female speed in a single group movement. (**c**) denotes male speed versus female speed in a single Load-bearing group movement.

3.2. Group Cohesion

Here, the cohesiveness of the group was examined according to the time interval of the group members arriving at the shooting floor. The larger the arrival time interval of group members, the more dispersed the group was and the lower the cohesiveness was. The reverse was also true. Figure 5 shows the cohesiveness of groups in each scene. The cohesion levels of the 13 pedestrian groups were 1.13 s, 1.21 s, 0.53 s, 0.80 s, 0.92 s, 0.48 s, 1.81 s, 1.46 s, 0.82 s, 1.07 s, 1.12 s, 1.53 s, and 0.79 s. The cohesiveness of groups was relatively concentrated, and only a few groups, such as groups F, N, and S, move dispersedly. The influence of group size and weight-bearing on group cohesion was not obvious, and the group cohesion was mostly concentrated at about 1 s.

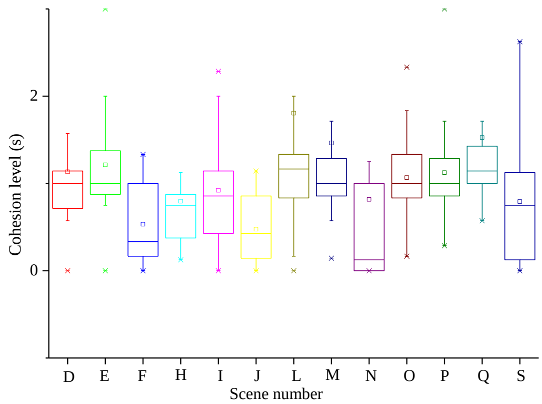

Figure 5. Group cohesion in different scenes. The scene numbers are consistent with those in Table 1.

In order to explore the correlation between group speed and group cohesion, we listed all groups' movement data in scenes D, E, F, H, I, J, L, M, N, O, P, Q, and S. Figure 6 shows that, generally, the higher the group cohesion was, the stronger the interference of group members' movement space was and the easier it was to affect the speed of the group. Therefore, we conducted a hypothesis test analysis pf the two groups of data. The correlation coefficient of group velocity and cohesiveness was found to be about 0.16, which proved that group velocity and cohesion had no significant correlation in stairwell movement. It can be seen in Figure 6 that the movement speed of the group in the stairwell was mostly concentrated at 1.0–1.4 m/s and the cohesion of the group was mostly concentrated at about 1 s, which provided a reference for the establishment of subsequent models.

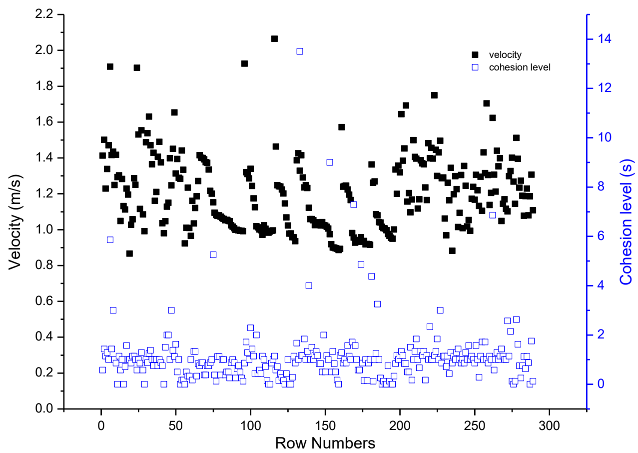

Figure 6. The relationship between group velocity and cohesion.

3.3. Evacuation Time

After analyzing the movement characteristics of a single group, we analyzed the macrocharacteristics of crowd movement. Figure 7 shows the evacuation time for 60 pedestrians to reach the third floor. At the beginning, some individuals quickly evacuated, but the people at the back of the group could not follow closely because of their own movement speed or the movement speed of the people around them. Therefore, there was a platform period at the beginning of the curve, and this platform period also intermittently appeared in the whole process of the experiment. Group G, group H, group I, and group J represented groups of pedestrians walking without any weight, and group K, group L, group M, and group N represent pedestrians bearing weight, as detailed in Table 1. The evacuation times of the eight groups were 179 s, 180 s, 175 s, 185 s, 196 s, 199 s, 197 s, and 191 s. On the whole, it took a longer time for the crowd bearing weight to evacuate. The fastest evacuation time was 175 s, and the slowest time was 199 s. This difference of 24 s proved that light loading is conducive to the evacuation process.

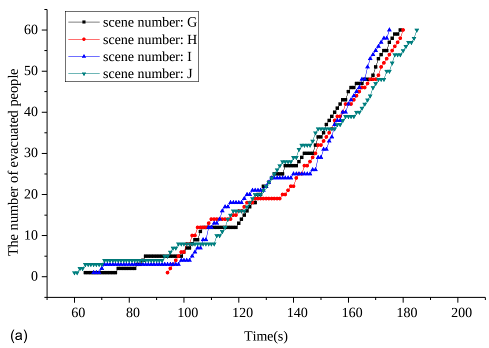

Figure 7. The evacuation time of different scenarios. The scene number is consistent with that in Table 1. (**a**) shows the number of evacuated people over time of scene G, scene H, scene I and scene J, and (**b**) shows the number of evacuated people over time of scene K, scene L, scene M and scene N.

3.4. Temporal and Spatial Distribution of Evacuation Process

By analyzing the overall evacuation times of all pedestrians, we found that there was a long time interval among some pedestrians, especially in the early and middle stages of evacuation; see Figure 8. The reason for this kind of intermittent evacuation may be that the width of the stairs limited the crowd's transcendence behavior, so the group members had to keep in close contact. In addition, comparing the evacuation time–space diagrams of the eight cases showed that there was little difference in the slope of the movement curve, which may have been related to the evacuation width of the stairwell of the residential building.

3.5. The Number of People in the Staircase Evolves over Time

Regardless of the kind of scene or stairwell, the number of pedestrians generally first increased and then decreased to a significantly low value, which was consistent with the results obtained by NIST researchers [38]. The number of people in the stairwell fluctuated or even dropped to zero when they just entered the stairwell. After that, with the continuous entry of follow-up pedestrians, the number of pedestrians reached a stable state, and then the total number of pedestrians continued to decline with the continuous departure of pedestrians. In Figure 9, we can clearly see the maximum number of people in the stairwell. The larger the number was, the higher the density of people was, the more crowded the stairwell was, and the greater the probability of stampede risk was. The total number of people in the stairwell from the 17th floor to the 15th floor was the largest, reaching about 30 people in the scenario of people without any load, as shown in Figure 9a–d, while the maximum number of people could reach about 25 people in the scenarios of people with load, as shown in Figure 9e–h. In addition, the curve shows a spiral rising state in the rising process, indicating that there was an intermittent evacuation state in the evacuation process again, which was the same as the findings regarding the temporal and spatial distribution of evacuation processes.

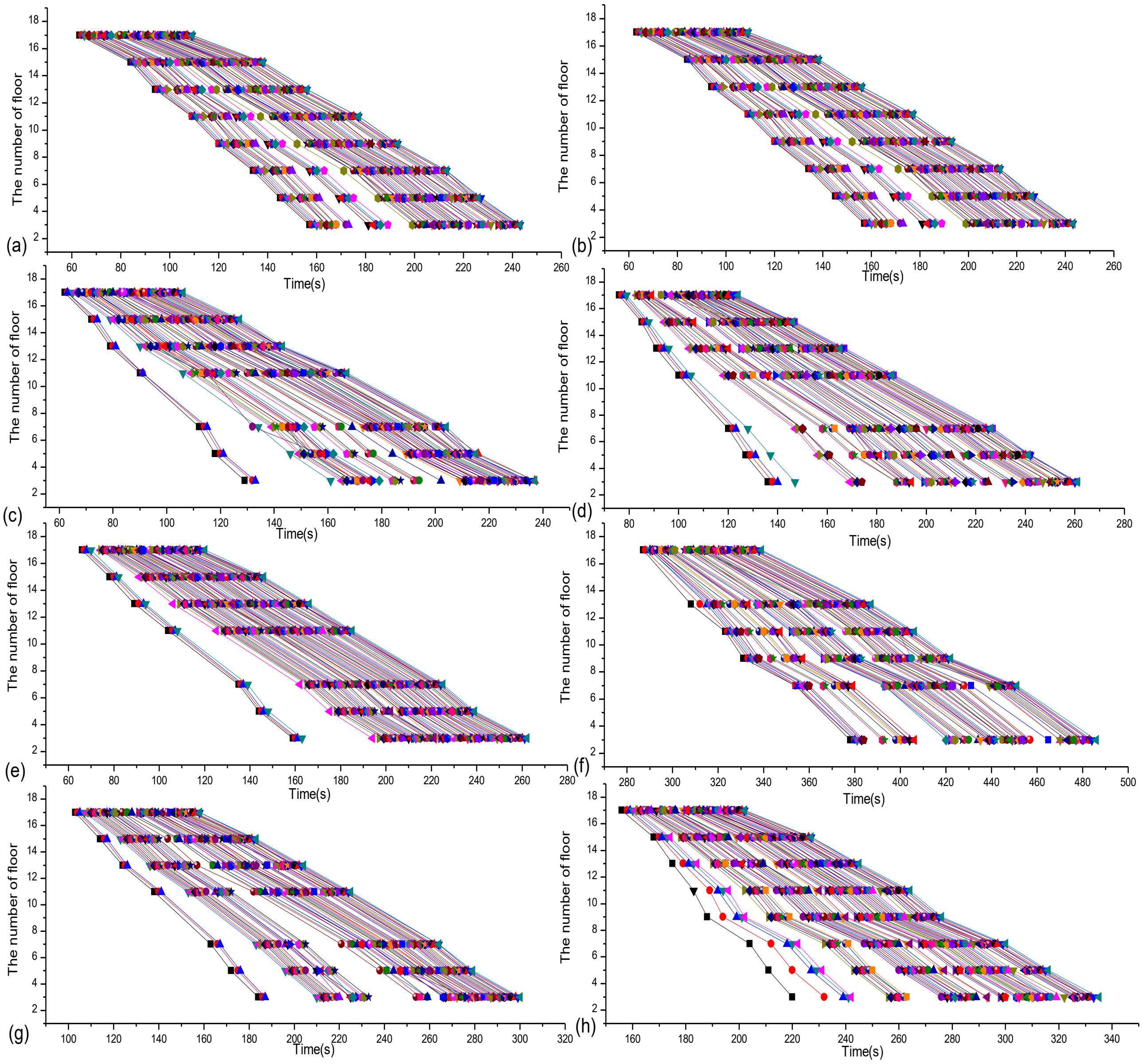

Figure 8. Temporal and spatial distribution of different evacuation processes. (**a**) shows the crowd movement with individuals (60 pedestrian I). (**b**) shows the crowd movement with the dyads (60 pedestrian I). (**c**) shows the crowd movement with the triads (60 pedestrian I). (**d**) shows the crowd movement with four-person groups (60 pedestrian I). (**e**) shows the crowd movement with individuals (30 pedestrian I, 15 pedestrian II and 15 pedestrian III). (**f**) shows the crowd movement with the dyads (30 pedestrian I, 15 pedestrian II and 15 pedestrian III). (**g**) shows the crowd movement with the triads (30 pedestrian I, 15 pedestrian II and 15 pedestrian III). (**h**) shows the crowd movement with the 4-person groups (30 pedestrian I, 15 pedestrian II, and 15 pedestrian III).

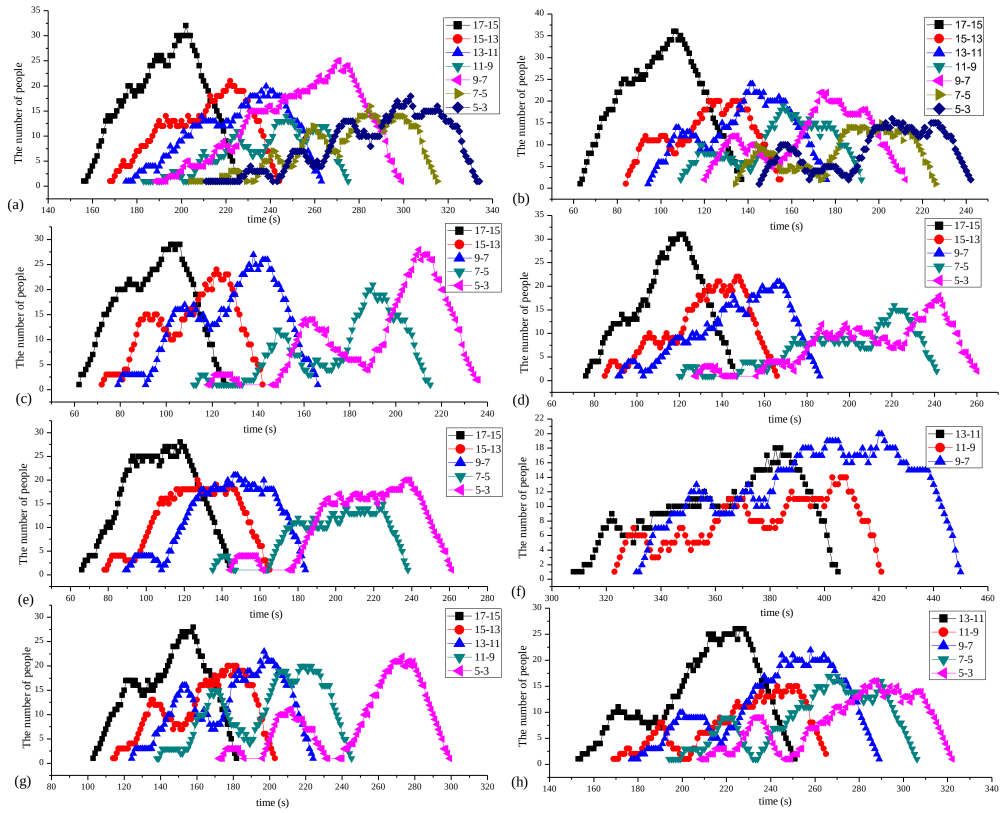

Figure 9. The time-varying curves of the number of people in every two stairwells under different scenarios. (**a**) shows the crowd movement with individuals (60 pedestrian I). (**b**) shows the crowd movement with the dyads (60 pedestrian I). (**c**) shows the crowd movement with the triads (60 pedestrian I). (**d**) shows the crowd movement with four-person groups (60 pedestrian I). (**e**) shows the crowd movement with individuals (30 pedestrian I, 15 pedestrian II and 15 pedestrian III). (**f**) shows the crowd movement with the dyads (30 pedestrian I, 15 pedestrian II and 15 pedestrian III). (**g**) shows the crowd movement with the triads (30 pedestrian I, 15 pedestrian II and 15 pedestrian III). (**h**) shows the crowd movement with the 4-person groups (30 pedestrian I, 15 pedestrian II, and 15 pedestrian III).

3.6. The Fundamental Diagram

A fundamental diagram shows the relationship between flow and density or between speed and density, which is widely used in the analysis of road and pedestrian systems [39]. In order to analyze the fundamental diagrams of pedestrians in the experimental staircase area, it was necessary to calculate the movement speed of pedestrians and the corresponding crowd density. Then, we mainly studied the relationship between pedestrian density and speed in the process of evacuation. Our fundamental diagrams showed the empirical relationship of crowd density–flow rate or density–velocity under specific structures and also provides basic parameters for building structure design and pedestrian evacuation management. The following figures show fundamental diagrams of pedestrian movement in different scenes.

In order to compare the fundamental diagrams of different scenes, the scale ranges of the coordinate axis in the above eight subgraphs were unified, as shown in Figure 10, which enabled us to compare the differences of the fundamental diagrams in different scenarios. According to the overall trend, with the increase in the number of pedestrians (that is, the increase in stairwell pedestrian density), the speed of pedestrians presented a downward trend, which was consistent with previous studies [40]. Because the velocity here represents the overall velocity, not the local velocity, the distribution of crowd speed in the low-density scene was larger. On the other hand, the similarities between Figures 10a and 10b–h were calculated with a hash algorithm [41] as 53.48%, 54.67%, 58.93%, 54.78%, 54.62%, 56.92%, and 60.05%, respectively. These findings show that there were some differences in the fundamental diagrams of crowd movement under different evacuation scenarios, but the differences were not significant, so crowd movement seems to weaken individual heterogeneity in movement difference.

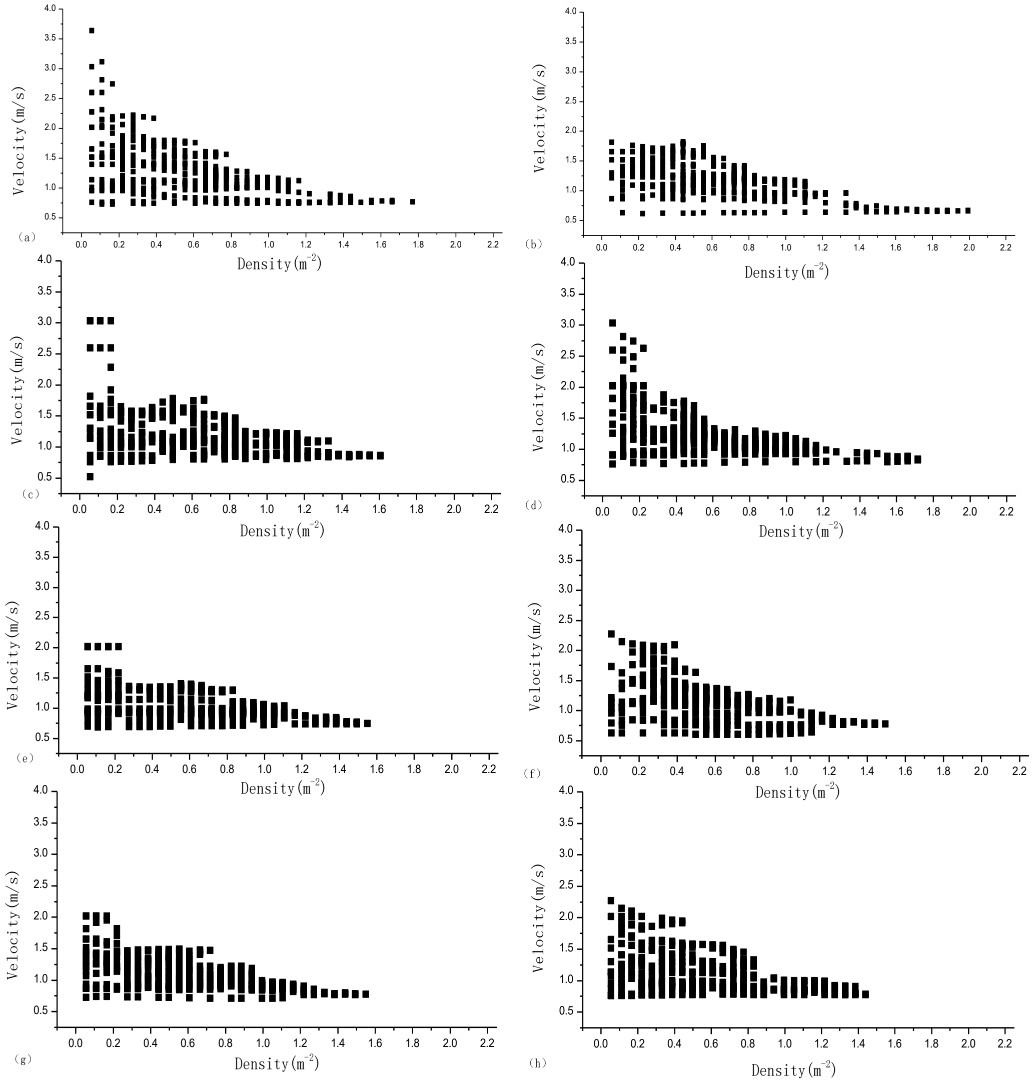

Figure 10. Fundamental diagrams of velocity–density. (**a**) shows the crowd movement with individuals (60 pedestrian I). (**b**) shows the crowd movement with the dyads (60 pedestrian I). (**c**) shows the crowd movement with the triads (60 pedestrian I). (**d**) shows the crowd movement with four-person groups (60 pedestrian I). (**e**) shows the crowd movement with individuals (30 pedestrian I, 15 pedestrian II and 15 pedestrian III). (**f**) shows the crowd movement with the dyads (30 pedestrian I, 15 pedestrian II and 15 pedestrian III). (**g**) shows the crowd movement with the triads (30 pedestrian I, 15 pedestrian II and 15 pedestrian III). (**h**) shows the crowd movement with the 4-person groups (30 pedestrian I, 15 pedestrian II, and 15 pedestrian III).

3.7. The Relationship between Pedestrians' Velocity and the Order of Pedestrians Entering the Stairwell

The order of pedestrians entering the stairwell refers to the sequence of pedestrians entering the evacuation stairwell. It can be seen in Figure 11 that in all evacuation scenarios, the pedestrian speed first decreased and then maintained a relatively stable state with the increase in the order of entering the stairwell, i.e., the speed of the pedestrians entering the stairwell in the back of the group was generally not greater than that of the pedestrians in the front, which indicates that the overtaking behavior of people in stairwell evacuation was relatively insignificant, which was consistent with Zeng's research [42]. In this experiment, the total width of the stairs was 1.05 m, and the staircase could accommodate up to two people at the same time, which led to a smaller chance for pedestrians to pass each other. As seen in Figure 11a,b,g,h, due to the influence of their own movement ability or groups, the speed of pedestrians showed a decreasing state during the evacuation process, which indicated that a slow speed of pedestrians in the front of a group may become a movement obstacle for pedestrians at the back of the group. From the beginning of the 20th pedestrian entering the stairwell, the density of pedestrians No. 20–60 in the stairwell was relatively stable and pedestrians rarely engaged in overtaking behavior, so the pedestrian speed remained relatively stable.

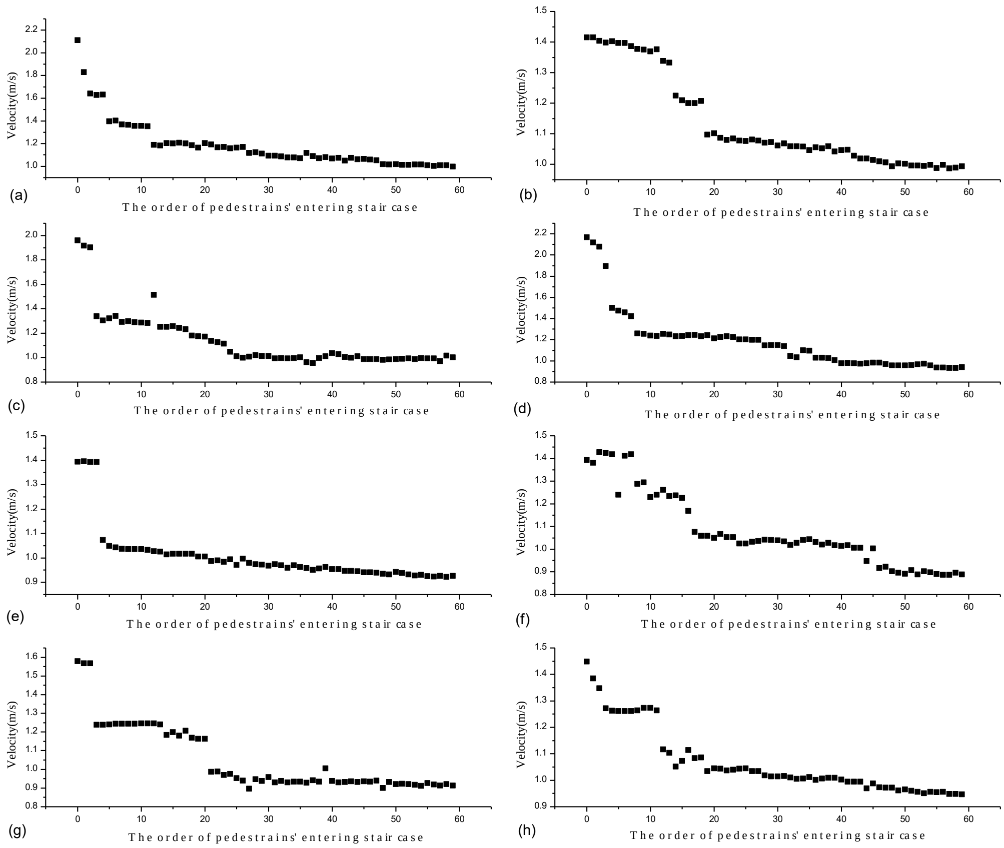

Figure 11. The distribution of pedestrian speed with the order of entering the stairwell in different scenes. (**a**) shows the crowd movement with individuals (60 pedestrian I). (**b**) shows the crowd movement with the dyads (60 pedestrian I). (**c**) shows the crowd movement with the triads (60 pedestrian I). (**d**) shows the crowd movement with four-person groups (60 pedestrian I). (**e**) shows the crowd movement with individuals (30 pedestrian I, 15 pedestrian II and 15 pedestrian III). (**f**) shows the crowd movement with the dyads (30 pedestrian I, 15 pedestrian II and 15 pedestrian III). (**g**) shows the crowd movement with the triads (30 pedestrian I, 15 pedestrian II and 15 pedestrian III). (**h**) shows the crowd movement with the 4-person groups (30 pedestrian I, 15 pedestrian II, and 15 pedestrian III).

4. Summary

With the frequent fires in high-rise residential buildings in China, the evacuation process of the group in the building is worthy of further study; thus, a group evacuation experiment in a high-rise residential building was carried out to simulate different realistic scenarios in this manuscript. At the same time, the loading evacuation of pedestrians in the group was considered. An 18-scene evacuation experiment was conducted in a high-rise residential building to study the movement of different groups in its stairwell. Two types of evacuation experiments were carried out: single group movement experiments and a crowd with groups evacuation experiment. The former was mainly used to study the micromovement characteristics of different types of groups in the stairwell, and the latter was mainly used to analyze the macromovement characteristics of different types of groups in the stairwell.

It is probable that most of the experimental pedestrians evacuated with the help of stair handrails and that some male volunteers even jumped multi-level stairs, which accelerated the evacuation process. The speed of 93% of pedestrians exceeded 1 m/s, and regardless of the type of group, the average speed of the crowd was more than 1.2 m/s. The speed of pedestrians was significantly higher than that found in previous studies. The pedestrian group movement mode and load factors were found to affect the speed of the group. For most cases, the speed of men was significantly higher than that of women, especially in scenarios with more constraints. Although the influence of group size and weight-bearing on group cohesion was not obvious, group cohesion was mostly concentrated at about 1 s. Additionally, it was found that group velocity and cohesion had no significant correlation with stairwell movement.

On the whole, it took a longer time for the crowd bearing weight to evacuate than the crowd without weight. The fastest evacuation time was 175 s, and the slowest time was 199 s. This difference of 24 s proved that light loading is conducive to an efficient evacuation process. Analyzing the temporal and spatial distribution of different evacuation processes showed that there was a long time interval between some pedestrians, especially in the early and middle stages of evacuation. The slope of the movement curve, i.e., the speed of the crowd, was more affected by the stairwell structure than by group movement pattern and weight bearing. Regardless of the kind of scene and stairwell, the number of pedestrians generally first increased and then decreased to a very low value, reaching about 30 people in the scenario of people without any load, while the maximum number of people reached about 25 people in the scenario of people with load. Based on the relationship between pedestrian speed and the order of entering the stairwell, the speed of the pedestrians entering the stairwell in the back of the group was generally not faster than that of the pedestrians in the front, which indicated that people in the stairwell rarely engaged in overtaking behavior.

These research results provide support for the further understanding of group movement in stairwells and subsequent modeling. The findings in our experiment are very meaningful for the study of pedestrian evacuation in stairwells, but there are still some areas that need to be improved and supplemented in our research. For instance, there was only one stair size in all our experiments, so we could not study the influence of stair size on group motion, which is worth further study.

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