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Minireview

State-of-the-art high-rise building emergency evacuation behavior

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ABSTRACT

Emergency evacuation in case of an emergency is a crucial problem in high-rise buildings, as many occupants are in a limited amount of space. To improve building safety design and evacuation strategies, it is essential to understand how individuals behave during an evacuation in high-rise buildings. This paper surveys the recently available literature on evacuation in high-rise buildings with the following objectives: (1) to review the high-rise building evacuation experiment methods; (2) to review the wayfinding and impact factors in horizontal evacuation; and (3) to review the individual and crowd behaviors in vertical evacuation. The review highlights the application of the virtual reality technology in evacuation experiments and the two-side effect of the group behavior in high-rise buildings. Future research should focus on quantitative pre-evacuation behavior study, the elevator's assistant function, and the impact of group relations on evacuation. As the height of high-rise buildings continues to increase, individual characteristics, such as mobility issues and fatigue, warrant further study.

Contents

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1. Introduction

The population continues to grow in large and medium-sized cities throughout the world, though the area available in urban environments remains limited. To accommodate this growth, high-rise buildings have developed out of necessity. According to the National Fire Protection Association [1], buildings with a height of more than 75 ft (approximately 23 m) are defined as high-rise buildings. In contrast, the definition of high-rise buildings in China is slightly different: according to the Code for Design of Civil Buildings in China [2], residential buildings higher than 10 stories and other civil constructions higher than 24 m are classified as high-rise buildings.

Currently, most high-rise buildings share similar problems of over-construction and over-dwelling, leading to a rapidly-spreading fire that is more difficult to extinguish when it occurs [3,4]. During an emergency evacuation, most people use the stairs to evacuate, causing congestion. Besides, elderly residents and slow-moving children reduce the evacuation flow speed, further exacerbating congestion and slowing the stair evacuation process [5], which may eventually lead to stampedes. Therefore, the research on high-rise building evacuation behavior during emergencies is both significant and necessary. Some scholars have done some reviews on evacuation behavior [4–8]. However, other scholars have given attention to the evacuation in high-rise buildings and have obtained some interesting conclusions. Consequently, this review concentrates on human behavior in the case of high-rise building evacuation and the research methods used throughout the last ten years.

To complete the review, the literature was retrieved from several databases, primarily Web of Science (2020) and Google Scholar, with the keywords including *evacuation behavior*, *high-rise building evacuation*, *evacuation experiments*, and *fire evacuation behavior*. The framework of this paper is shown in Fig. 1 and the review results are as follows. Section 2 describes the experimental method of high-rise building evacuation research. Section 3 provides information regarding horizontal evacuation including the perception of guidance, leader–follower behavior, herding behavior, and impact factors. Section 4 discusses vertical evacuation, which includes stairs, elevators, refuge floor, groups, cooperation and competition. The related conclusion is provided in Section 5.

2. Experiment method

At present, studies regarding high-rise building emergency evacuation experiments are mainly from the following three aspects: incident analysis, evacuation drill, and controlled experiment. Virtual reality (VR) and augmented reality (AR) technology are widely used in conducting evacuation experiments. Some researchers have also discussed the corresponding data validity and transferability by conducting experiments.

Emergency evacuation data can hardly be completely collected (even at all) and practical fire tests cannot be conducted, especially in high-rise buildings. Therefore, two common sources of evacuation data are the incomplete evacuation data from actual fire incidents and the data from evacuation experiments without the risk of fire.

2.1. Incident analysis

One of the sources of evacuation data that has been previously used is the incomplete evacuation data from actual fire incidents. The evacuation of September 11, 2001 was one of the most significant emergency evacuations of high-rise buildings in modern times, and it was also one of the largest full-scale building evacuations of people in modern times. The studies on the World Trade Center (WTC) attacks, which are of great value, can be taken as an example.

According to the information in A Hybrid, Energy-Efficient Distributed clustering approach (HEED), the behavior and experiences of six evacuees of Towers 1 and 2 were chosen to learn about their fire safety awareness and the details about emergency evacuations. The behaviors from the incident can reveal the true reflection of evacuees. Even based on incomplete data, numerous conclusions regarding evacuation safety in high-rise buildings have been drawn. Although their validity cannot be proven by an event that only happened once, the results are still informative for buildings safety design [9].

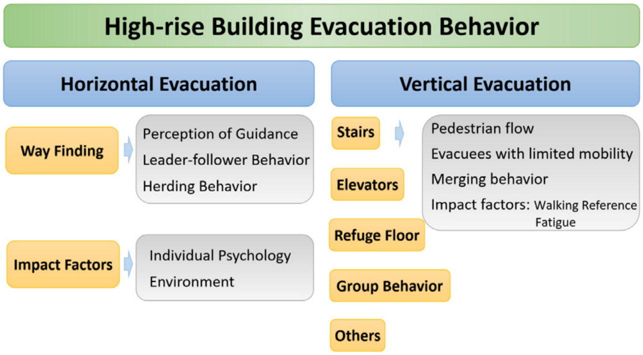


Fig. 1. The outline of high-rise building evacuation behaviors.

2.2. Evacuation drill

Global evacuation drills are either evacuation drills with pre-notification or evacuation drills without pre-notification (i.e., the time of the evacuation is not disclosed). Recently, scholars have scrutinized the data from building evacuation drills [10], such as those in shopping malls [11], supermarkets [12], and hotels [13]. The collected data can be used to verify simulation models [14]. For example, Kobes et al. [15] held evacuation drills without pre-notification to study route choice behavior. Participants were not informed of the evacuation time, which made the results more similar to actual events. Shi et al. summarized and analyzed data obtained from fire incidents and drills, providing strong support for the emergency evacuation model [16]. It is generally believed that evacuation drills without pre-notification are approximately closer to actual evacuations, because evacuees are less anxious about their safety in evacuation drills in which they are pre-notified. In recent years, the evacuation of children and older individuals in multi-story buildings has attracted more attention. Poulos et al. analyzed students' evacuation behaviors based on a school drill [17]. They established an agent-based model to simulate the evacuation process, and validated the simulation model according to the fire drill data.

A partial evacuation drill requires the individuals within certain parts of a building to evacuate rather than all of the people in the entire building to evacuate. In some ultra-high-rise buildings, global evacuation drills cannot be conducted because of the variety of occupants' jobs and the overall building design; hence, partial evacuations are widely applied in ultra-high-rise evacuation drills. Several studies have discussed controlled experiments with evacuations in high-rise fires [18–21]. In these experiments, three basic evacuation parameters (velocity, density, and flow) and the pedestrian flow in high-rise buildings were under discussion. As early as the 1930s, researchers began experimenting with pedestrians and evacuation using this method. Research mainly analyzed the basic movement parameters of pedestrian flow – namely, density, velocity, and flow – by observing the pedestrian flow in public buildings, and analyzed their interrelationships. However, high-rise building evacuation problems can only be reflected from certain perspectives due to limitations pertaining to experimental scale and fire settings.

2.3. Controlled experiment

Unlike global and partial evacuation drills, during a controllable flow test, a channel [22], a bottleneck [23,24], a T-type passage [25], or a temporary ring channel set-up at a stadium is chosen as the experimental field [26,27]. Experimental designers dispatch flows with various fluxes passing through a certain position. Cameras and Radio Frequency Identification (RFID) equipment in certain positions or the entire experimental field can be used to collect data on pedestrian flow. Boltes et al. did several experiments to analyze density waves, stop-and-go waves, jamming and clogging, lane formation, and bottleneck flow, concluding most of the typical evacuation partial scenes within high-rise buildings and the method of data analyzing [28]. Li et al. modeled the evacuation process in a primary school, and the results can be used to mitigate the effects of a fire disaster in school [29]. Kim et al. studied the behaviors of older people based on 2015 National Online Survey of Caregivers [30]. Fang et al. carried out several experiments to study the evacuation behaviors of 5-6-year-old Chinese children [31]. Li et al. also studied the evacuation process of pre-school students [32]. In a controllable flow test, in addition to examining flow speed, density, and flux, group behaviors can also be studied, including overtake behavior and herd behavior [33–35].

2.4. VR/AR experiment

With the development of technology, VR experiments are gaining an increasing amount of attention. VR technology is a computer simulation system that can create and emulate a virtual world, which can be used in high-rise building evacuation research. With computer-generated three-dimensional (3D) dynamic interactive scenes, users can immerse themselves in the created environment and provide feedback on it.

As early as 1997, VR equipment was applied to the evacuation behavior research in Japan [36]. The scholar received similar evacuation preferences from the virtual experiment and a real drill. In recent years, VR technology has been able to create a much more realistic experiment environment and has been widely used to research pedestrian evacuation [37], such as exit selection [38], path finding [39], reaction to evacuation signs [40], and reaction to stressful environment simulations [41]. The virtual world provides the chance to conduct some dangerous and expensive evacuation experiments. For example, evacuation elevators have not been allowed as an evacuation route during an emergency in many countries, though they must be considered in high-rise building evacuation. As a result, Andrée et al. established a VR model to study exit choice and waiting time for evacuation elevators [42]. It is found that green flashing lights can make more participants choose the elevators as egress, and the general waiting time is either limited to less than 5 min or longer than 20 min. Based on the virtual environment, Bourhim et al. simulated a fire scene using Unity 3D game engine and compared the results with the data from real fire conditions to test the effectiveness of the information provided by the VR system [43]. The correlation coefficient between the virtual data and the real one is 0.9783 ($p < 0.001$), which confirmed the efficacy of the VR technology for research on people's pre-evacuation behavior under fire. Cao et al. conducted a virtual indoor museum to study the route choice behavior [44]. Some participants explored under the control condition while others were under the fire condition. It was found that participants under the fire emergency condition spent more time in finding their way to exit the museum than those under the control condition, and those participants who explored the virtual museum actively traveled longer in completing the task than those who did it passively. In addition, some evaluation methods have been researched to test the rationality of VR emergency evacuation, and results show that the proposed model can efficiently simulate the crowd movement and agent behavior in dynamic environments [45–48]. Scholars have also used a VR platform on individual evacuation behavior [49,50]. Li et al. conducted an experiment that showed that over 74% of choices can be predicted by considering the distance to exits and the number of pedestrians using exits, and the average speeds of pedestrians around exits do not substantially contribute to choices [51].

Besides, AR technology also plays an important role in evacuation experiments. In this field, AR technology is mainly used to develop applications for simulating the evacuation environment, as well as to enhance the realism and engagement of the evacuation drills. Lovreglio illustrated that all the AR applications were developed to affect the movement stage during building evacuations by reviewing 12 selected papers related to the applications of AR for building evacuation. He also concluded that the goal of AR application is not only to simulate the environment, but also to navigate building occupants during building evacuations and connect the evacuation simulation to the real environment [52]. Some scholars have studied the threats during the evacuation process based on augmented drills. Kawai et al. and López et al. focused on the impacts of digital fires, smoke, injured occupants, and cracks generated by an earthquake and building fire [53,54]. Iguchi et al. and Mitsuhara et al. also augmented their earthquake drills with the damage generated, as well as with the digital building occupants the participants are supposed to interact with [55,56]. Ahn and Han developed a navigation system that could potentially be used for any type of disaster [57], while López proposed a smart system for fire emergencies supporting occupants depending on their characteristics and fire location [54]. The latest type of application is to visualize building evacuation simulations, with Lochhead and Hedley providing a new approach to link evacuation simulations with the real-world context of the built environment [58].

VR technology and AR technology are still developing rapidly and the immersive feeling is continuously being promoted. It is possible to replace the real experiment, which is dangerous, expensive, and unavailable, and provide various valuable data that is hardly acquired from real life. However, some problems have yet to be solved. Firstly, the gap between the VR/AR experiments and emergency events still exists, limiting the reliability of these studies. Secondly, the evaluation method of the VR/AR environment immersion is incomplete and the similarity between the virtual scene and the real environment is not quantitative.

2.5. Data validation

To discuss the corresponding data validity and transferability, some researchers make a contrast between different aspects of evacuations while conducting a series of experiments. Tordeux et al. developed, trained, and tested several artificial neural networks for the prediction of pedestrian speeds in corridor and bottleneck experiments. The estimations are compared with those of a classical speed-based model. The results show that neural networks can distinguish the two facilities and significantly improve the prediction of pedestrian speeds [59]. Cao et al. studied the fundamental diagrams for uni-, bi-, and multidirectional flows at corridors, and crossings were investigated by a series of evacuation experiments. Significant differences related to capacity were determined by comparing the data of uni-, bi-, and multidirectional flows and literature data with classical methods [60]. Sano et al. introduced a novel and simplified mathematical model for the calculation of evacuation times on stairs that takes into account the impact of merging flows. By studying a hypothetical model case of a 10-floor building evacuation and comparing the results of the new model with those of SimTread's evacuation simulation model, they discussed the advantages and limitations of the new model [61]. Zhao et al. conducted a series of real-life human evacuation experiments considering different types of obstacles. They compared the density profiles of pedestrians based on the trajectories and the Voronoi method. In this way, they found the essential physical mechanism behind the evacuation efficiency enhancement while placing an obstacle actually significantly decreases the density level in the crowded region by effective separation in space [62]. These studies revealed the underlying mechanism of evacuation performance enhancement and discussed the corresponding data validity and transferability while considering different types of behavioral data. However, data validation is still an aspect lacking in research, requiring additional attention in future studies.

All the experimental methods mentioned above can be applied to the evacuation of high-rise buildings in theory; however, global evacuation drills may face more difficulty in practical applications. There are other evacuation experimental methods. Taking animal-involved experiments as an example, some researchers have studied the evacuation behaviors through the experiments of animals and insects [63,64], especially the behaviors in a state of panic [65,66]. Few details are given here because these methods are atypical in high-rise building evacuations.

In addition, there are three problems when conducting experiments and collecting data. (1) Most studies are conducted inside ordinary buildings; consequently, there are little data regarding the evacuation of high-rise buildings. In general exercises, individuals are prohibited from using the elevator to evacuate. As a result, experiments using elevators during an evacuation need to be specially conducted. (2) For each group of subjects, given physical, emotional, and financial constraints, the repetition of experiments is limited (e.g., an experiment can only last for 1.5 h; otherwise, participants will become tired or irritable, leading to meaningless results). Thus, very few studies meet the requirements of analyzing various factors according to traditional experimental design theory in finite experiments, and the experimental process is plagued by confounding factors due to the complex experimental objects — human beings. (3) There is a distinct difference between an evacuation experiment and an actual fire evacuation. During an experiment, it is necessary to control the experimental process but not to control it excessively; thus, the existing experimental methods and designs call for improvement.

3. Horizontal evacuation

The evacuation process in high-rise buildings can be divided into two parts: horizontal evacuation and vertical evacuation. This section focuses on pedestrian behavior in the horizontal evacuation process, in which route choice plays a vital role.

Normally, the structure of high-rise buildings is complex and confusing with many turns and obstacles. It is not easy for evacuees to find an exit to the staircases. In the internal evacuation, route choice has a strong influence on the time cost and the final evacuation efficiency. There are three typical behaviors involved in the horizontal emergency wayfinding: perception of guidance, leader–follower behavior, and heading behavior. Besides, other impact factors are discussed in this section, such as individual psychology and environmental characteristics.

3.1. Perception of guidance

As evacuation signs are the most important information indicators for indoor evacuation, pedestrians interact with the signs and make the evacuation decision after processing the signals [67,68]. The interaction process between pedestrians and signs has been divided into three phases: perceiving the sign, detecting the sign, and following the sign [69]. Various factors influence the interaction process, including objective features of the signs, cognitive abilities of pedestrians, environments of the buildings, and so on [70,71]. Researchers usually study the interaction between signs and pedestrians with real experiments and VR experiments, and are mostly combined with questionnaires.

As for the real experiments, Jeon et al. investigated the influence of exit signs designed with various features and under different visibility conditions on the wayfinding speed of evacuation in a complex underground subway station [72]. They claimed that larger sized signs improved evacuation speed, and changes in features of exit signs had more influence under better visibility. Wong and Lo analyzed the visibility of exit signs by reviewing the size of the sign content, and the inclusion of graphics or colors, as well as lighting conditions, and age of the observers [73]. Survey results showed that green exit signs were highly visible, and pedestrians detected signs better when the signs were located high and at reduced illumination. Chen et al. simulated a pedestrian evacuation process under bad visibility conditions and discovered that evacuation signs with illumination could significantly optimize the process and decrease evacuation time [74]. Galea et al. suggested that the dynamic nature of the proposed emergency exit sign greatly enhanced the effectiveness of emergency exit signs, making them significantly more likely to be detected [75]. Olander et al. analyzed the exit signage design based on the Theory of Affordances. It is found that, when compared to a red background, the recommended background color for dissuasive signage is green (with red LED X-markings) [76]. Fu et al. tested the influence of emergency signage on building evacuation behavior based on both experiments and a questionnaire survey [77]. Ding carried out evacuation experiments with wearable eye-tracking devices. The results showed that the effect of the green "arrow" evacuation sign is the best. The effect of Low (corridor) signs works better than those of High (room) signs, but the signs of Low (corridor) could be blocked by the front evacuees [78].

On the other hand, VR technology is imported to verify the evacuation sign effect. Arias et al. manufactured a virtual environment of European Organization for Nuclear Research (CERN) and compared the pedestrian detecting and following choices under the red flashing signs, dynamic signs, and robot information guidance [79]. Tang et al. constructed an experiment space with VR and simulated three scenarios: without signage, with old-version signage, and with new-version signage [80]. After the experiments, the average wayfinding time and gender effect were compared. Kinateder et al. immersed the experiment participants in a virtual room with two exits and contrasted the effect under different sign colors [81]. It was found that the behavior differs from the verbal report. Cai et al. studied the feasibility of mixed reality equipment HoloLens in the research on evacuation signs [82]. Olander et al. [83] used questionnaire surveys and VR experiments to investigate the effectiveness of dynamic signs. They found that emergency signs with flashing lights have the potential to improve the effectiveness of information acceptance and wayfinding behaviors, but the impact of different colors in flashing lights varies. For example, red flashing lights increase the sensory detection of dissuasive signage.

In most of the existing evacuation models, it is normally assumed that all of the pedestrians would follow the sign direction as long as the sign exists. But sometimes not all of the pedestrians detect the signs, and some even refuse to follow the signs after they see them. Fu et al. [77] and Xie et al. [84,85] tend to consider the probability of detecting and following the signs by experiments. However, the surrounding people's influence on the detection and following probability was not included and requires further study.

3.2. Leader–follower behavior

Most people are followers during an evacuation [86,87]; they tend to not react to danger at first and instead keep waiting for others to act. If a leader guides properly, evacuation efficiency improves. Li et al. identified opinion leaders through an analysis of the social network structure during an evacuation experiment. They found that in the evacuation process, most of these "opinion leaders" played the role of "leader" [88]. Many people will find their own family, children, or friends when evacuating, and choose to evacuate with people to whom they are close. Fang et al. established an agent-based model to study the leader–follower behavior in particular scenarios: lining up in counter-flow, queuing, and collective mobility [89]. Concentrating on the direction decision-making in crowd evacuation, Haghani and Sarvi found that a strong tendency to copy direction choices of the crowd could substantially hinder the process of evacuations and increase the risk of casualty [90].

It is found that evacuation direction choice is related to leader and follower behavior. In the complex high-rise buildings, wrong escape direction will waste much valuable evacuation time and potentially result in death. Studying the leader–follower formation and the opinion spread will surely help with evacuation management and promote evacuation efficiency.

3.3. Herding behavior

Herding behavior refers to individuals in high-pressure situations who are influenced by group behavior and abandon their personal views to become consistent with the majority behavior. Herding behavior is entirely blind and the pedestrian has no exact leader to follow. The route choice comes from the group and not from some special evacuees. In contrast, the leader–follower groups can choose a different exit from the whole group. That is the main difference between leader–follower behavior and herding behavior. In 2000, Helbing used the social force model to simulate the phenomenon of conformity [91], and discussed the characteristics of blind conformity; many other scholars followed. As research has revealed, conformity is the main behavior in an evacuation, especially when the evacuee's vision is limited and evacuation information is obscured due to smoke, fire, inadequate lighting, or other factors [12]. Current research on herd behavior has found that panic is the root cause of conformity. In simulation studies, it is regarded that herding is negative and conformity is adaptive. But in the process of an emergency evacuation, appropriate herd behavior can alleviate an individual's anxiety, and conformity is a much more convenient means of making decisions for those who are unfamiliar with an evacuation environment. Therefore, herd behavior should be viewed dialectically.

3.4. Impact factors

(1) Individual psychology

In a fire incident, people's psychological stress rises because the situation is beyond their control [92]. Excessive mental stress can destroy an individual's cognitive ability and reduce his or her reaction speed. Research has shown that in an emergency, fear can be diffused [93,94], and that blind following expands rapidly, resulting in unreasonable or non-social behaviors among large numbers of people, such as disorder, congestion, and so on. Personal congested behavior in a large group of people will influence the surrounding people and form a density wave, leading to the stop-and-go phenomenon, where stampede accidents can easily occur. It is necessary to prevent and control crowds in the event of an emergency. Understanding individual evacuation behavior can help promote evacuation efficiency.

In many publications, it is claimed that the experiments are conducted in a situation without panic, indicating that panic has a noticeable influence on the research and the evacuation in panic deserves additional and deeper study in the future [95,96]. Pedestrians' emotional state in emergencies will be impacted by their knowledge about the emergency and environment. In a familiar environment, such as the home or office, it is easier for evacuees to find the best route and leave the building quickly. If they were in a strange environment and facing a novel emergency, wayfinding would be much harder and the behavior could be irrational due to emotion [97]. Generally, most pedestrians have little experience in evacuation practice, especially for high-rise buildings. In addition, for those working or living in a high-rise building, they are only familiar with the route to elevators and only part of the buildings is used in their daily life. The route to the staircases and safety exits is not obvious for them, which may lead to stress and panic [98].

(2) Environment

Besides the individual factors, an emergency environment has a noticeable influence on wayfinding. Pedestrians decide the evacuation route to avoid fire and smoke. If the corridor is filled with smoke, the route decision will be changed [99–101]. Similarly, the lightness also influences the pedestrian's route choice according to the natural phototaxis [102].

In an emergency, pedestrians' individual behavior differs greatly compared to normal circumstances [103]. Whether they succeed in fleeing the scene within the available safe egress time (ASET) depends on two factors: people's mental and behavioral reaction to the incident and whether the evacuation design is reasonable. From the beginning position to the outside of the building, the horizontal distance is much less than the vertical distance in high-rise building evacuation. Thus, the evacuation time of horizontal evacuation is also shorter than vertical movement time. In the following section, the majority of the review focuses on vertical evacuation.

4. Vertical evacuation

Egress choices include stairs, evacuation elevators, and other new evacuation aids, and people often behave differently during an evacuation in various egress choices. In this paragraph, different egress choices and related findings are discussed. In most buildings, stair evacuation is the most traditional and still the only recommended way to evacuate. However, with the increasing height of high-rise buildings, staircase congestion is more likely if members of a crowd all take the stairs to evacuate. The stairs are not as accessible for elderly, weak, sick, disabled, or very young evacuees [104]. Furthermore, in high-rise buildings, the use of stairs to evacuate will inevitably lead to pedestrian fatigue. Most people are on high-rise floors, which reduces the efficiency of crowd evacuation. In this case, the use of elevators during an evacuation has become more popular [105–108]. Elevators can be used as an ideal auxiliary method for evacuation. In a report from the WTC attack [109], some survivors succeeded in evacuating with elevators. Thus, it is crucial to study how to use elevators to evacuate efficiently. Besides, other abnormal egress choices are also included in this part.

4.1. Evacuation behavior in stairs

In the vertical stairs, pedestrian flow characteristics are often different from a horizontal evacuation and the discrete steps limit the evacuation speed. In addition, apart from spiral steps, every two stairs need to be connected by a platform, where people need to complete the side turning, leading to a slower speed. Many scholars pay attention to the evacuation speed in stairs.

It was not until the WTC attacks that high-rise building evacuation attracted public attention once again. Many researchers investigated the accident and discovered that the speed of the survivors during stair evacuation was less than 0.3 m/s, indicating low evacuation efficiency [105]. Besides, some people with limited mobility were not only slow in their own evacuation, but they also affected the speed of evacuees behind them [110]. The tolerant range of the arrival rate is narrower with the higher-storied buildings; also, the blocking probability occurs sooner than expected [111].

4.1.1. Pedestrian flow

Fu et al. conducted experiments with different sizes of singles and pedestrian groups, which showed that both step time and step width for groups with larger size are significantly higher during descending movements [112]. Köster et al. found that pedestrians are generally slower upstairs than downstairs when on the stairs only, while the situation is opposite when on the landing. The average speed on the stairs including the landing is 0.736 m/s downward and 0.704 m/s upward. The average speed on the stairs excluding the landing is 0.615 m/s downward and 0.531 m/s upward. The average speed on the landing is 0.853 m/s downward and 0.900 m/s upward [113]. Kretz et al. tested evacuees' speed on the stairs at two different slopes: 35.1° and 22.2°. They found that with a 22.2° slope, the average downstairs speed was 0.90 m/s, fluctuating from 0.58 to 1.44 [114]. Proulx et al. carried out an evacuation experiment in a 13-story building where the lights were dimmed. Results showed that under different illumination conditions, the average moving speed of evacuees was between 0.40–0.66 m/s [115]. Yeo et al. collected data about pedestrian moving speed from a large station in Singapore and found that the average speed of men and women going downstairs was about 0.42 m/s and 0.36 m/s, respectively [116]. Peacock et al. collected data from eight evacuation drills and found that higher floors and a longer evacuation distance did not lead to a slower speed during crowd evacuation [10,117]. Hoskins studied the characteristics of the interaction between the individual and a group in his thesis and analyzed crowded evacuation data from multiple buildings. It was found that the average speed of stair evacuation was between 0.44 m/s and 0.72 m/s [118]. Fu et al. employed a multigrid model to understand pedestrian dynamics in counter flow and the result showed that emotion propagation makes a markedly decrease in average speed which reflected the phenomenon of "faster is slower" [119]. Ma et al. carried out a series of experimental studies in the 470-m-high section of Shanghai World Financial Center. In the first experiment, six people evacuated from the 101st floor to the first floor by stairs. The participants' ages were between 21 and 62 years old. The evacuation time was approximately 30 min at a speed of 0.28 m/s. In the second experiment, 177 people were set on each floor from the 12th to 17th floors, and when they evacuated to the refuge layer (6th floor), they continued to use the stairs to complete the evacuation until they reached the 1st floor. The authors presented the evacuation time of each person in the picture but did not give a concrete numerical value of everyone's evacuation speed [26].

Table 1
Evacuees' speeds in the references.

Source	Mean Velocity (m/s)	Age	Gender	Slope	Distance	Scenario
Fruin [125] 1971 US data	0.60 0.67 0.67 0.76 0.88 1.01	Over 50 Over 50 30–50 30–50 Under 30 Under 30	Female Male Female Male Female Male	26.5° & 31.9°	1 floor	Experiment
Averill [105] 2005 US data	0.20	–	–	–	–	9/11 Attack WTC Tower
Galea [110] 2012 US data	0.29				–	9/11 Attack WTC North Tower
Kretz [114] 2008 German data	0.90(0.58-1.44)			22.2°		Experiment with 6people
Proulx [115] 2010 Canadian data	0.40–0.66	18–65			13 floors	Experiments with reduced lighting
Yeo [116] 2008 Singaporean data	0.42 0.36	– –	Male Female	Vertical travel speed Vertical travel speed	Short stair Short stair	Experiment Experiment
Peacock [10] 2012 US data	0.44 ± 0.19 0.44 ± 0.15 0.56 ± 0.12 0.52 ± 0.10	–	–	32.5° 36.9° 32.5° 33.1°	10 floors 18 floors 24 floors 31 floors	Drills
Peacock [117] 2017 US data	0.44 ± 0.19 [0.10m/s±0.008,1.7m/s±0.13]				14 buildings	
Hoskins [118] 2011 US data	0.72 ± 025 0.59 ± 0.23 0.61 ± 0.12 0.48 ± 0.20 0.44 ± 0.15			32.5° 32.5° 38.2° 36.9° 33.1°	24 floors 10 floors 62 floors 18 floors 30 floors	Drills
Kholshevnikov [120] 2012 Russian data	0.32–1.16	<3–7				Experiments
Capote [121] 2011 Spain data	[0.28-0.77]±0.14 [0.29-1.39]±0.29 [0.63-1.46]±0.18	12–16 8–12 12–16		33.5° Vertical travel speed 33.5° Vertical travel speed 33.9° Vertical travel speed	15 steps 15 steps 8 steps	Drills
Larusdottir [122-124] 2011, 2012 Danish data	0.69–0.81 0.13–0.58	9–15 3–6		30°-34° 30°-33°		Drills
Ma [21] 2012 Chinese data	0.28 0.59–0.62	– –	– –	– –	101 floors Less than 20 floors	Experiment with 6people Two experiments
Fang [19] 2012 Chinese data	0.81	–	–	–	8 floors	Experiment
Choi [126] 2014 Korean data	0.83 0.74	23.4 23.4	Male Female	32.5° 32.5°	50 floors 50 floors	Experiment Experiment
Huo [127] 2016 Chinese data	0.74–0.98	Young Students		28.6°	9 floors	Experiment
Zeng [128] 2017 Chinese data	0.50 ± 0.14	Young Students		28.6°	9 floors	Experiment

Some researchers have studied the evacuation of minors. Kholshevnikov conducted evacuation studies on children aged 3–7 and found that their moving speed on the stairs was between 0.32 m/s and 1.16 m/s [120]. Capote respectively studied the moving speed of minors aged 8–12 and 12-16 years on stairs and found it to be [0.29–1.39] ± 0.29 m/s and [0.28–0.77] ± 0.14 m/s, whereas the participants only moved 15 steps in the study [121]. Larusdottir conducted a study on young children aged 3–6 and teenagers aged 9–15 and found that the average speed downstairs was 0.13–0.58 m/s and 0.69–0.81 m/s [122–124]. These data are presented in Table 1.

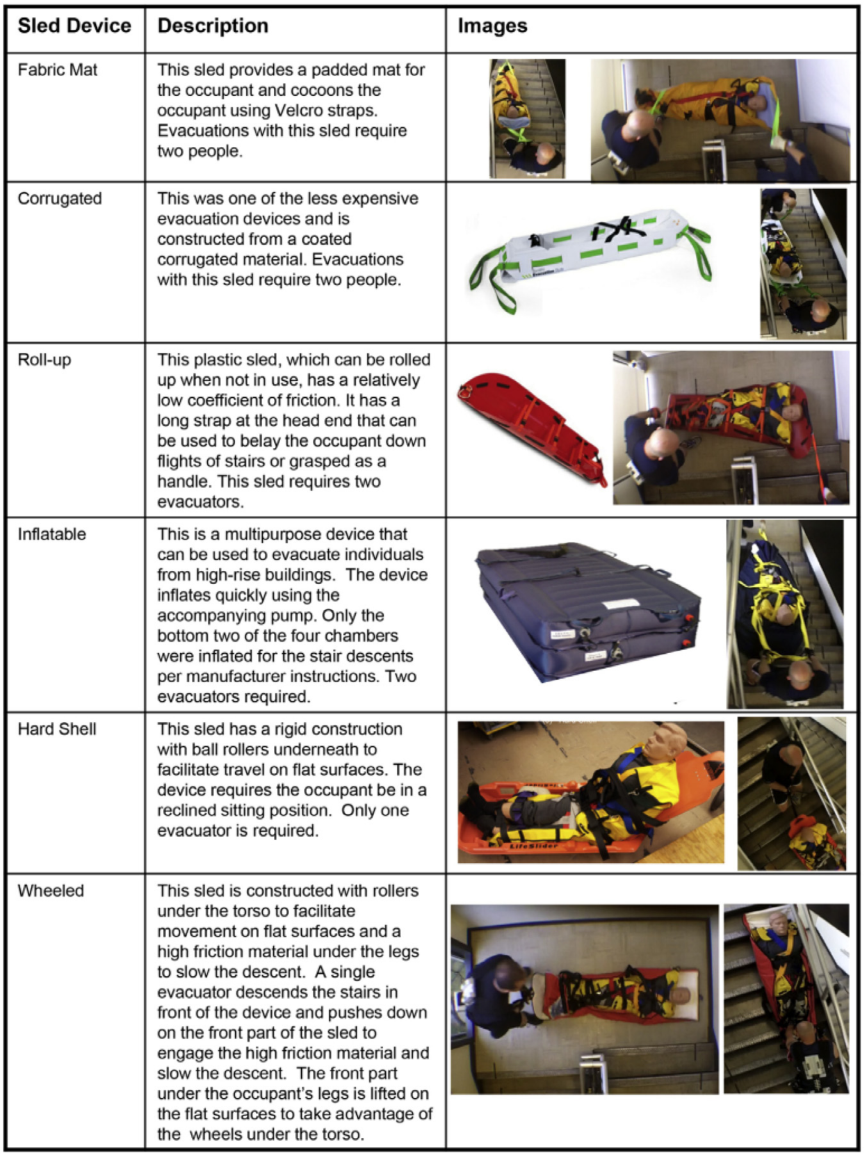
4.1.2. Evacuees with limited mobility

It is difficult for people with limited mobility to use the stairs to evacuate. They often need help from others because it is challenging to evacuate alone when using a wheelchair or a cane. Boyce and Shields [129] studied the evacuation capacity of people with limited mobility when using accessory tools and not, respectively. When someone helps a disabled person to evacuate, the helper and evacuee form a small group; Shields et al. [9] studied the impact of such groups during the evacuation process. Different assistant tools are also researched and can be divided into two types: a stretcher [130], on which people with limited mobility need to be lying and then fixed; and seat type [131], that has handles and is convenient for rescuers to lift. The first and second categories of auxiliary evacuation tools are shown in Figs. 2 and 3.

4.1.3. Merging behavior

Merging behavior occurs on the stair landings in high-rise buildings when the occupants walk into the stairwell and merge with the downstream crowds. Merging location, merging flow, and local density have an obvious influence on the evacuation speed. Merging behavior on each floor of the staircase platform is important in the evacuation of high-rise buildings. Pedestrian behavior will affect the speed of pedestrian flow, which in turn affects overall evacuation time.

As early as 2008, Galea et al. developed a C++ software to simulate merging behavior, including Occupant, Movement, Behavior, Toxicity, and Hazard sub-models. Conflict behavior was introduced to describe the merging behavior [132].



Sled Device	Description	Images
Fabric Mat	This sled provides a padded mat for the occupant and cocoons the occupant using Velcro straps. Evacuations with this sled require two people.	
Corrugated	This was one of the less expensive evacuation devices and is constructed from a coated corrugated material. Evacuations with this sled require two people.	
Roll-up	This plastic sled, which can be rolled up when not in use, has a relatively low coefficient of friction. It has a long strap at the head end that can be used to belay the occupant down flights of stairs or grasped as a handle. This sled requires two evacuators.	
Inflatable	This is a multipurpose device that can be used to evacuate individuals from high-rise buildings. The device inflates quickly using the accompanying pump. Only the bottom two of the four chambers were inflated for the stair descents per manufacturer instructions. Two evacuators required.	
Hard Shell	This sled has a rigid construction with ball rollers underneath to facilitate travel on flat surfaces. The device requires the occupant be in a reclined sitting position. Only one evacuator is required.	
Wheeled	This sled is constructed with rollers under the torso to facilitate movement on flat surfaces and a high friction material under the legs to slow the descent. A single evacuator descends the stairs in front of the device and pushes down on the front part of the sled to engage the high friction material and slow the descent. The front part under the occupant's legs is lifted on the flat surfaces to take advantage of the wheels under the torso.	

Fig. 2. Stretcher type auxiliary evacuation tools [130].

Boyce et al. studied the confluence ratio on the stairs and found that the number of origin pedestrian flows and the number of new arrivals were approximately the same [133]. They also collected evacuation data from three different buildings and studied the influence of staircase and floor connection location structure and evacuation on confluence [133]. Ronchi et al. found that the greater the number of people on the docking platform, the longer the distance they traveled. The authors thus suggested that the phenomenon be evaluated in advance using data analysis and modeling [134]. Huo et al. extended the original lattice gas model by considering inner-side walk preference, turning behavior, and different desired speeds. The simulation results have the same tendency as the empirical data [135]. After that, Huo et al. conducted two different experimental scenarios [136]. The speed of participants walking through two adjacent floors and the space–time distribution were discussed. It was found that the longer time intervals between participants occur because of the bottlenecks caused by slow movement individuals and participants who stand in front of the queue accelerate just before merging with participants coming from upstairs. Huo et al. found that when a person in the front of the pedestrian flow suddenly accelerated before entering the confluence [127], it may be because a person in the main pedestrian flow thought he or she had the right of way [137]. Xu and Song simulated a crowd evacuation process on the stairs via computer and found that congestion usually occurred on the transfer platform, resulting in a decline in evacuation speed [14]. Takeichi et al. studied driving factors behind convergence in stairs, including density, convergence direction, and whether the door

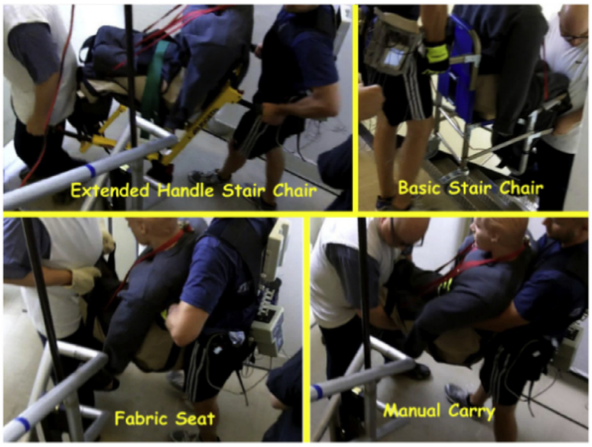


Fig. 3. Seat type auxiliary evacuation tools [131].

was closed when entering the stairs [138]. Besides, Zeng et al. carried out several experiments to study how distribution ratio and illumination influences merging behaviors [139,140].

It is clear that merging behavior is attracting more and more attention. Summarizing the current research, it can be found that when people come into the landing, merging behavior naturally occurs. However, waiting for merging is very normal in real life due to the aversion to crowds. The personal decision-making of merging needs further research.

4.1.4. Impact factors

(1) Walking preference

Walking preference is an important factor affecting evacuation behavior and mainly includes the following three aspects [141,142]. (1) When pedestrians go downstairs, they will walk down the inside as much as possible because the distance is shortest and they can hold the handrail while descending. (2) When on the steps, pedestrians tend to keep a certain distance from the people in front of them, called dynamic space requirements. If a person in front suddenly stops, the people behind also need enough room to stop. (3) When going downstairs, with the effect of gravity and step height, pedestrians rarely go backwards or sideways. They mostly only move straight ahead, to the front left or right.

(2) Fatigue

Personal physiological conditions vary from one to another, with the main influencing factors being gender, age, obesity, and disability (or inconvenience). Though, no matter the type of crowd, it is possible to face the problem of physical fatigue during an evacuation. In high-rise and ultra-high-rise buildings, this problem has occurred during many fire incidents including the WTC terrorist attacks [110,143,144], as well as the 2010 Shanghai high-rise apartment 11.15 fire incident [145]. Many survivors felt tired. In the interview with the WTC survivors [110], as shown in Table 2, most survivors reported stopping at least once during the evacuation. The team of researchers from the present study investigated 42 survivors of the 11.15 fire incident in Shanghai [145], more than half of whom were over 50 years old; 47.6% said they were slow in the evacuation process. With the consideration of fatigue, it takes 71.4% longer for all persons to enter the stairs and 87.2% longer to evacuate. With the consideration of the merging flow, fatigue has little impact on the inflow, while it takes 84.2% more time to evacuate with the consideration of fatigue [146].

Some people walked slowly because of their age or physical discomfort, while others are because of evacuating with their family. Denny et al. summarized the rate of slowing down due to fatigue from the experiments on healthy people and found that after walking 1.5 km, the tired speed slowed to 65% of the original speed [147]. Notably, slow people were a barrier to the evacuees behind them. Weariness, therefore, has a great impact on high-rise building evacuation. Fatigue is a factor that cannot be ignored in building design. The rate of slowing down due to fatigue is shown in Table 3, which was derived from experiments on healthy people [147].

4.2. Evacuation behavior in evacuation elevators

In recent years, the use of elevators for evacuation has gained popularity in many countries [148]. For example, the Building and Fire Codes of the International Code Council (ICC) [149], and the Building Fire Code of the American Fire Protection Association [150], now allow evacuees to evacuate using elevators in cases of fire and other emergency situations. There have been several successful cases using elevators for evacuation [105,106,145,151] [152]. But when it comes to using an elevator to evacuate during an emergency, there are still several problems that need to be addressed.

When using elevators to evacuate in emergency situations such as fire, the most important issue is elevator safety [153]. As the elevator is moving, negative pressure is generated in the elevator shaft, resulting in the chimney effect. Therefore,

Table 2
The number of stopping time from the survivors in WTC 9/11 event.

Floor area	No stopping	Stop at least once	Total
High floor: 61–90	7 13%	47 87%	54 100%
Middle floor: 31–61	5 11%	41 89%	46 100%
Low floor: 1–30	6 25%	18 75%	24 100%
Total	18 15%	106 85%	124 100%

Table 3
Ratio of people slowing down during evacuation.

Walking distance (m)	The ratio of the tired speed to the original speed (%)
Less than 100	100.00
From 101 to 200	99.85
From 201 From 400	89.42
From 401 From 800	75.80
From 801 From 1500	69.82
From 1501 From 3000	65.72

the elevator evacuation system requires basic functions of fire protection, heat protection, and smoke prevention [154,155]. The fire may disrupt the power system in a building, so it is necessary to ensure the elevator's power supply and to design the elevator system to be waterproof [156–158]. In addition, the design of evacuation elevators needs to ensure protection against earthquakes, to protect emergency communications, and to prevent the transmission of pollutants [159]. Therefore, if operated properly, elevators can be used as a guarantee of timely evacuation in high-rise buildings to help people evacuate [160–164]. At the same time, a smoke control system for the elevator system in super-tall buildings should be evaluated carefully based on an evacuation strategy and effects of different groups of occupants and their familiarity with the evacuation route in evacuation [165].

In many countries, it is prohibited to encourage people to use elevators, so, for most people, it is difficult to accept the idea of using elevators in cases of fire. Though, with the premise that firefighters have provided guidance and training, most people on higher floors are open to using elevators to evacuate [166]. People may face crowding and other problems when using the elevator to evacuate due to the narrow space inside of an elevator [167].

It is necessary to conduct an in-depth study of individuals' evacuation behavior when using elevators to take into consideration the elevator system design, elevator scheduling, and elevator waiting room [168–170]. For example, during an emergency, when an elevator is overloaded, the last person may not be willing to leave the elevator, which means the door cannot close and the car will be delayed. Some scholars have used online and offline questionnaires to investigate the proportion of evacuees who would be willing to use the elevator to evacuate from various floors [170–173].

For the behavior of each person entering and leaving the elevator, an evacuation experiment was conducted [169]. For an elevator with a load of 1000 kg, the time that an evacuee takes to the elevator (6 s) is much shorter than that of opening and closing the doors (15.4 s). More attention should be given to the time of opening and closing the doors than that of entering the elevator. Nevertheless, relevant research is still limited. In an actual evacuation process, the number of people evacuating with elevators, the waiting time of evacuees, the waiting circumstances, and the factors affecting their decisions and behavior have not been solved and require further study [174].

During the evacuation process, many people tend to start evacuating at the same time, so it is best to choose an open area as an evacuation elevator's pickup location, such as the refuge floor [175], and some buildings have done so [161,176]. The refuge floor is a floor in high-rise buildings that provides fire shelter for evacuees, is never used for commercial or residential purposes, and does not store any flammable or explosive materials. It is essential to set up refuge floors or refuge rooms in high-rise buildings to provide temporary shelter for people waiting to be rescued or to take a brief rest [177]. Studies have pointed out that in a high-rise building fire, it is recommended that people take a break every 18 floors [26]. China's Building Design Fire Code has given the key requirements about refuge floors in high-rise buildings [178].

In high-rise buildings, there may be many elevators and elevator groups. The question of how to improve the scheduling of a group of elevators has been given attention [179]. Some studies on the use of elevators in evacuation have summarized the elevator evacuation strategy and designed a new method that considers the refuge floor/room in ultra-high-rise buildings [179,180]. However, there is scarce research regarding individuals' behavior on the refuge floor, so further analysis is needed.

Fig. 4. The refuge floor in the fire experimental high-rise building in Sichuan Province.

4.3. Evacuation behavior on refuge floor

High-rise buildings have many floors and large personnel density, so that such a large number of people evacuating at the same time is bound to cause congestion. Moreover, the evacuation time of people on higher floors is longer, and the spread speed of smoke is much faster than the movement speed of people. Therefore, it is very necessary to set up refuge floors or refuge rooms in high-rise buildings. A safe refuge mode can provide temporary refuge places for people in the fire to wait for fire rescue. As shown in Fig. 4, the fire experimental high-rise building in Dujiangyan, Sichuan Province is equipped with a refuge floor within which there are no flammable materials and facilities, and an evacuation elevator is set.

The study indicates that in high-rise building fires, it is recommended to take a rest for every 18 floors evacuated [181]. In addition, fire prevention and smoke prevention facilities must be installed on the refuge floor, which can effectively block fire and smoke to a certain extent and ensure the safety of people on the refuge floor within a certain time limit. No flammable items should be placed on the asylum floor. Everyone on the refuge floor should have 0.3 square meters of space. On the refuge floor, there will be multiple staircases and elevators to allow for a secondary evacuation. The staircases on the refuge floor were designed separately. The staircases connecting the upper and lower floors of the refuge floor were disconnected and the pedestrians entering from the upper and lower floors had to leave the staircases and then enter another stairway to continue descending [182]. In fact, there are relatively few studies on refuge floor, and it presently lacks relevant experimental support.

4.4. Group behavior

Gerges et al. investigated the human behavior under a situation of fire in high-rise residential buildings [183]. It was found that occupants have limited knowledge and skills on how to deal with fire emergencies. Consequently, pedestrians in residential buildings, schools, or office buildings tend to escape in groups during emergency evacuation [184]. It turns out that up to 70% of people in a crowd are actually moving in groups, such as friends, couples, or families walking together [86]. The interactions among the groups have much more impact on the crowd structure and evacuation dynamics than individual behavior. Leader–follower behavior, small-group behavior, and cooperation behavior are the three typical group behaviors in high-rise building evacuation.

Friends, family, and other close teams naturally form small groups due to the social relationship among the evacuees. The interactions among small groups are more remarkable than those among individuals. According to social relations theory, this behavior is called clustering. Small groups are the result of cluster behavior; during the evacuation process, these groups are characterized by spatial position, velocity, and synchronization in decision making.

Moussaid et al. observed a free-walking population with 1500 people in natural motion and examined the structure change in different local density. The insights demonstrate that the communicative and social interactions among individuals lead to group organization and are significant for the crowd dynamic [185]. Fu et al. found that information transmission cannot be useful all the time by conducting experiments through simulation under four-way pedestrian situations. They found that the value of drift strength and pedestrians' motion behavior highly impact on the crowd dispersion process [186]. Bode et al. used simulations to analyze the effect of small groups on the evacuation time of individuals and groups. The results showed that small groups increased evacuation time and reduced evacuation efficiency. The small groups were mainly formed in two stages: at the beginning of the evacuation and the time when they were close to the exits [187]. Li et al. assessed small groups by analyzing the social network of evacuated groups and studying the evacuation behavior of small groups in evacuation experiments [188]. Zheng and Cheng introduced the game theory model into the field model. They examined people's competitive and cooperative behavior based on psychological factors [189], as well as groups' evolution and cooperation in the presence of small groups [190]. In addition, small groups have been found to affect elevator evacuations. Previous studies have revealed that small groups are more inclined to participate in collective activities, but some small groups generally cannot enter the elevator due to limited elevator space and load, thus extending the time it takes for the elevator door to close.

At present, research on small-group behavior is mainly focused on either an actual disaster accident or clustering behavior in this phenomenon based on its characteristics and related qualitative research. Additionally, computer simulations can emulate the process of small-group behavior. However, there is still a lack of field observations related to the size and quantity of small groups in evacuated populations. The factors leading to small-group formation are also worth analyzing. Due to the small group formation, cooperation behavior and competition behavior are common, especially in the residential high-rise building evacuation. Particularly, the impact of cooperation and competition behavior on evacuation efficiency is not consistent.

Cheng and Zheng established a computational model to understand the cooperation behavior in crowds with different level emergencies [190–193]. It is observed that higher emergency results in lower cooperative frequency and the cooperative frequency will be maintained at a high level for a non-emergency situation. In addition, the size of a group has negative impacts on the average evacuation speed. If the evacuees tend to cooperate with each other, the evacuation efficiency will be increased. However, the conclusion is not always right. In some situations, selfish behavior may result in high evacuation efficiency, for example, during crossing an exit [194]. Gao et al. compared the impact of different level competition on the evacuation flow rate [195]. Ding et al. conducted a series of experiments about the cooperation behavior during elevator evacuation and found that the cooperation behavior in a small group will delay the total evacuation time [196,197]. Nguyen et al. found that calculating the optimal room capacity to maximize exiting flow, strengthening the guidance of personnel flow during a time of crisis, and improving the visibility of exit routes are conducive to reducing the occurrence of catastrophic crowd events [198].

Cooperation behavior and competition behavior have a strong relationship with the social network in the crowds. Chen et al. quantified social relation by the social network method, and then the authors divided the participants into groups to study how social relationships influence the evacuation behavior, especially when the evacuees can use the elevator as an egress [199]. Besides, cooperation behavior and competition behavior are driven by the individuals' mental state and social relationships. The dynamic of the psychological state of the evacuees requires detailed study.

4.5. Others

In addition to the commonly used stair evacuation and the more recently popular elevator evacuation, there are other evacuation egresses in some high-rise buildings. For two adjacent high-rise buildings, it is possible to have a footbridge for occupants in the burning one to evacuate [200,201].

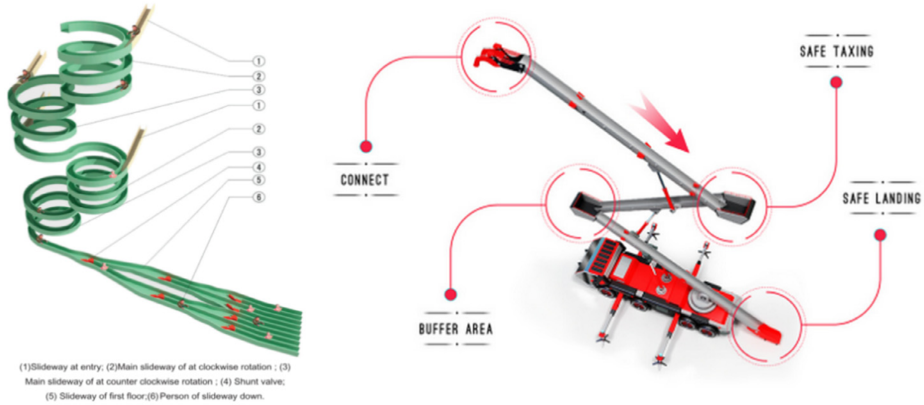
In recent years, some new forms of auxiliary evacuation have occurred, including the sideway evacuation system [202], as well as the life slide system [203]. The slide way evacuation system consists of a special spiral chute and shunt valve. As shown in Fig. 5(a), the evacuee can get to ground level quickly with the help of their own gravity without the need for additional power, nor do they need to expend their own physical strength. Therefore, the system is also suitable for people with limited mobility to evacuate independently. The life slide system consists of a crane, a slide, and a rescue ladder. As shown in Fig. 5 (b), in non-emergency conditions, the slides on the crane are folded and the crane can be lifted when needed. After connecting to the designated floor, the evacuees slide down. The buffer between the two slides can effectively slow down the desired speeds of the evacuees. The buffer also has designated areas for firefighters to conduct rescues. However, these new evacuation aids are seldom being used in official rescues and some of them are still in the design stage. At present, there is no research on using these new evacuation aids for human evacuation behavior.

Besides the other egress methods, signage and obstacles are also common in the process of high-rise building evacuation. Experiment results demonstrate that both signage detection and acceptance probabilities under individual conditions are larger than those under group situations because of the social influence in groups. High-placed signs have a positive effect on route choice, especially under individual conditions [77]. The non-parallel obstacle layouts (especially the concave layout) with larger longitudinal distance between obstacles are more beneficial to pedestrian movement when there are obstacles in corridors [204].

5. Discussion and conclusion

5.1. Individual physiological and psychological reactions during the evacuation of high-rise buildings

Unlike ordinary public places, the evacuation of high-rise buildings is mainly manifested in the characteristics of ''high''. ''High'' determines the evacuation is vertical evacuation, and the space of stairs is narrow, slender, and closed. These factors have a huge impact on the individual's physiology and psychology. It is necessary to study the physical characteristics of individuals on different floors, such as fatigue, tension, anxiety, panic, and other manifestations, as well as to study the microscopic attention behavior and risk perception behavior of individuals in staircases, elevators, and corridors. For physical reasons, some special people cannot evacuate well in high-rise buildings, so it is necessary to study the behavior characteristics of old, weak, sick, disabled, pregnant, and young people who are not suitable for evacuating high-rise buildings. Under the situation of congestion, these kinds of individuals in high-density crowds may push each other, even possibly causing a stampede accident. To reduce the risk of such an accident, the mechanism behind stampeding should



(a) (b)

Fig. 5. Schematic diagram of slide evacuation system and life slide system [202,203].

be fully understood. Moreover, a properly designed stair landing and staircase entrance location may also reduce the potential for an accident.

Until now, the results of most current studies have been based on evacuation experiments or drills. The virtual world can stimulate evacuees just like a real, accident and the pedestrian's reaction is more reliable than the controlled drills without the real emergency; however, the evaluation method of the level of similarity between the virtual and real situation needs more research and the immersion feeling needs further promotion. Particularly, due to limitations of technology, the interactions among the evacuees and environment are restricted in the virtual world, which may constrain the application of virtual technology. At the same time, a gap remains between experiments and actual emergency situations so that the effects of fire or other emergency situations on evacuees' psychological state and behavior are unclear.

5.2. Leader–follower behavior and small group behavior during an emergency evacuation of high-rise buildings

Pre-evacuation behavior has a notable influence on Required Safe Egress Time (RSET) and is related to the evacuee's danger perception and decision-making. Qualitative research is no longer sufficient. Precise and quantitative methods are needed to promote emergency evacuation management and pre-evacuation efficiency, which is significant for successful evacuation. Taking the support vector machine approach as an example, it can help to quantitatively investigate the pre-evacuation behavior of high-rise building occupants under various impact factors. High-rise building evacuation means long evacuation distance. It is common for evacuees to be tired after the first several minutes and then slowing down. For the back evacuees, front slow occupants are obstacles, which force all of the people behind these individuals to slow down, resulting in low evacuation efficiency. Reasonable emergency route design is required to solve the problem.

In a state of tension and panic, people tend to follow others and evacuate together in the form of small groups, and the social relationship in the evacuated group will exacerbate the formation of following behaviors and small group behaviors. How do leader–follower behavior and small group behavior form during the evacuation process in reality? How do social relationships in groups affect following behavior? What is the size of the small group during the evacuation process? Are the small groups and leader–follower behaviors different in various types of group evacuations? What is the speed of individuals and small groups during the evacuation process? These issues all need additional study.

5.3. Individual decision-making behavior when given the options of elevator and stair

According to traditional training, elevators are not allowed to be used during evacuations, so few studies have been conducted regarding elevator evacuation. Related studies are limited because of the prohibition of elevator escape in many areas. With the number of stories in buildings increasing, stair evacuation is not able to support the emergency evacuation and implementing the elevator into evacuation is necessary for the future. During the evacuation process, the individual needs to face the decision-making problem when using the elevator and the stairs together. The individual is affected by many factors such as physiology, psychology, and the external environment.

To explore the individual's decision-making behavior, the following issues need to be focused on: (1) The influencing factors of decision-making on individuals, such as the personality, physical state, social relationship, experience, and so on; (2) The choice of elevators, such as the proportion of people who choose elevators for evacuation, and the individual's acceptance of waiting time for elevators, the evacuation efficiency of elevators, and stairs; (3) The individual's decision-making process, including the individual's concerns and psychological changes in the process. Moreover, the influence of the spatial distribution of elevators and stairs on the evacuation behavior, the design, and the optimization of the system evacuation control system all require further study.

5.4. Optimization of high-rise building evacuation considering stairs, elevators, and evacuation behavior

According to the existing international standards, stairs are always the most traditional, most easily accepted, and currently the only legal evacuation method in an emergency evacuation of high-rise buildings. At present, the study of plane-based evacuation simulation models is relatively mature, while the study of stairs-based, vertical evacuation simulation models is relatively weak. The existing simulation results are not accurate compared with the actual evacuation results, because most simulation methods just consider the influence of the evacuation environment and personal factors such as stair structure and personal physiological conditions when the evacuation is considered. They fail to take into consideration the special psychological state of individuals in high-rise buildings – especially the social relationship among the groups – into account. The trend of evacuation simulation models is that individuals are getting closer to agents, but it is still difficult to integrate the natural and social attributes of people into high-level evacuation models. Therefore, the evacuation simulation model of high-rise buildings that integrates individual psychology and group social relationships needs further study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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