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Experimental study on characteristics of pedestrian evacuation on stairs in a high-rise building

Feizhou Huo [a,b], Weiguo Song [a,*], Lei Chen [a], Chi Liu [a], K.M. Liew [b]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230026, PR China
[b] Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon 999077, Hong Kong, China

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ABSTRACT

The characteristics of pedestrian movement down stairs from high-rise building influence the total evacuation time, the formation of congestion and even the safety of evacuees. In this paper two different experimental scenarios, which could be regarded as the phased evacuation and total evacuation respectively, were conducted on stairs in a high-rise building to investigate the evacuation process and pedestrian movement characteristics down stairs. The evacuation processes were recorded by video cameras, and the movement parameters were extracted from the video data. In experimental scenario one and two, the space–time distribution, the speed of participants walking through two adjacent floors and specific flow for participants through different stair landings were analyzed and discussed. Then, the fundamental diagrams for pedestrians in the two different evacuation scenarios were presented followed by the analysis of the influences of merging flow on pedestrian movement. It is found that the longer time intervals between participants occur because of the bottlenecks caused by slow movement individuals in experimental scenario one. In experimental scenario two, it is found that participants who stand in front of the queue accelerate just before the merging with participants coming from upstairs. Moreover, from the analysis of the fundamental diagram, we find that the merging flow influences pedestrians' movement down stairs, and the detailed egress facilities and evacuation processes should be taken into account when the functions of SFPE Handbook are used to predict the evacuation variables. It is also found that the speeds of participants from upstairs are reduced by the entry of participants from the corresponding floors during the merging time period.

1. Introduction

Recently, there have been a number of studies focused on human evacuation from high-rise buildings, especially since the "911" disaster (Averill et al., 2013; Fahy, 2013; Galea, 2012; Lovreglio et al., 2014; Ma et al., 2012b; Ronchi and Nilsson, 2014). With regard to the pedestrian evacuation in emergency, the evacuation process can be actually divided into three stages: the cue validation stage, the decision-making stage and the movement stage (Kobes et al., 2008). Some researchers investigated the fire safety of building evacuation in the cue validation stage and decision-making stage from the behavioral perspective (Kobes et al., 2010; Sime, 2001), while in the movement stage, the movement of people in corridors, on stairs and through doors were studied from the technological perspective (Fang et al., 2012; Ma et al., 2012b; Nelson and Mowrer, 2002) and the detailed information about pedestrian density and travel speed were collected.

For the purpose of predicting the evacuation process, different models have been proposed based on the rules summarized from different motion characteristics and basic behavioral issues (Kuligowski et al., 2010; Zheng et al., 2009). These models could provide valuable information about human behavior and movement during the evacuation, especially when it cannot be studied by experiments using real people (Ma et al., 2012a; Oven and Cakici, 2009). Specifically, they can provide insight into the consequences should certain behaviors be performed. When using these models, the model parameters such as pedestrian speed and area occupied by one person should be taken into account given that pedestrians in different countries with various cultural backgrounds might have different individual characteristics (Ma et al., 2010). To validate the accuracy of the evacuation models, the experiments about human evacuation were conducted in the stairwell of high-rise building (Fang et al., 2012), on ultra high-rise

* Corresponding author.
E-mail addresses: huofz@mail.ustc.edu.cn (F. Huo), wgsong@ustc.edu.cn (W. Song), clei@mail.ustc.edu.cn (L. Chen), roygain@163.com (C. Liu), kmliew@cityu.edu.hk (K.M. Liew).

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building (Ma et al., 2012b), on retail store (Cheng et al., 2009) and so on. Even though the experiments were conducted in normal conditions or approximately emergency conditions to ensure the safety of participants, which are different from the actual evacuation process, the results of the experiments are basis for predicting pedestrians' movement in a fire emergency (Nelson and Mowrer, 2002) and could provide fundamental parameters for evacuation models.

In high-rise building evacuations, stairs are most important emergency routes and in some cases they may be the only route, which are also bottlenecks of the evacuation, and have great influence on pedestrians' movement, especially in serious emergency situations. The size of the stairs, population density on stairs, merging of evacuees, individual characteristics (Proulx, 2007) as well as the counter flow of firefighters (Averill and Song, 2007) have significant influence on pedestrians' evacuation down stairs. Kratchman conducted an experiment in a six-story office building and the results demonstrated that the counter flow in the stairs will decrease the evacuation efficiency significantly (Kratchman, 2007). Moreover, it was found that pedestrians already on the stairs commonly feel that they have priority and are reluctant to allow pedestrians from floors to enter into the crowed stairs (Proulx, 2007). Xu et al. simulated the stair evacuation by using multi-grid model and the results indicated that the congestion occurs in the stair landings, which slows down the evacuation speed (Xu and Song, 2009). For the detailed analysis of the merging behavior, experiments in stairs of a building (Takeichi et al., 2005) were performed, and then the influencing factors about merging process were investigated, including the crowd density, directions of merge and whether the door joining a corridor to stairs is opened or closed, etc. However, there were only 27 participants in the experiments, which could not represent the merging process in the actual emergency evacuation. Galea et al. incorporated the representation of merging flow into an evacuation model (Galea et al., 2008), and according to the simulation results, the authors suggested that floors should be connected to the landings on the opposite side to the incoming stairs in high-rise buildings, which is beneficial to the overall evacuation. Boyce et al. have also investigated the merging behavior in stair landings through evacuation drills in three different buildings (Boyce et al., 2012), and highlighted the potential influence of geometrical location of floor relative to the stair, and population characteristics on merge patterns. The researchers in National Institute of Standards and Technology (NIST) have conducted numerous investigations on pedestrians' movement speeds in buildings with different stories (Kuligowski and Peacock, 2010; Peacock et al., 2012), which indicates the building egress features and provides a technical foundation for evacuation codes and standards requirements. The overall movement speed and local movement speeds were analyzed and discussed, and the results show that the local movement speeds vary widely within a given stairwell, ranging from 0.056 m/s to 1.7 m/s, which might be influenced by occupant characteristics and building characteristics, such as gender, age, motion capability of evacuees, width of stairs, and height and depth of stair tread. Moreover, Yang et al. compared the movement characteristics on stairs between daily movement of students when classes were over and an evacuation drill for college students (Yang et al., 2012). The results showed that the queuing behavior at stairs, merging flow at stair landings and subgroup behavior were found during the movement process.

Summarizing the previous studies (Boyce et al., 2012; Galea et al., 2008; Peacock et al., 2012), it can be found that the flow capacity and human behavior are two essential factors affecting the evacuation of occupants. It should also be noted that the flow capacity is influenced by the building components, such as the egress routes, the exits and the stairs. Human behaviors, such as the response and motion characteristics of evacuees, have great influences on evacuation process. However, there is little research focused on the movement process of pedestrians through stairs, especially the merging behavior at the floor-stair interface (Huo et al., 2014), including speed variation, specific flow on stairs and the influencing of merging on pedestrians' movement. Considering these features, we designed two experiments in the present study. The rest of this paper is organized as follows. In Section 2, the evacuation experiments are described. The results and discussion are presented in Section 3 followed by a summary of the findings in the last section.

2. Experiments

The evacuation experiments were conducted on a stair of 9-story high-rise building. The structures and dimensions of the building stairs are presented in Fig. 1. All the participants in the experiments were college students without movement impairments and chosen from different academies to avoid the communication between the participants during the experiments. There were 73 participants in the experiments and 72.6% were male. The average age, height and weight of the participants were 23.1 years old, 170.0 cm and 60.4 kg respectively.

Two different experimental scenarios were carried out: the first scenario referred to the phased evacuation that occupants evacuate from a specific floor, and the second scenario referred to the total evacuation that occupants evacuate from all floors in the building. To assist data processing, numbered hats were dispensed to participants who were informed to wear the hats during the evacuation processes, as shown in Fig. 2. The evacuation processes were recorded by five digital cameras, which were placed beside the stair landings of 9th, 7th, 5th, 3rd and 1st floors. Fig. 2 also shows the tracking process of the participant with the sequential number 24 on his hat in evacuation scenario one.

In the first evacuation scenario, all participants were initially distributed randomly on the corridor of the 9th floor, which was adjacent to the experimental stair. The participants moved into the stairs when received a signal of ''Ready, Go!'' During the evacuation process, they were required to move as their normal speeds for the consideration of safety.

In the second evacuation scenario, the merging flow was taken into consideration to investigate the characteristics of total evacuation. The detailed distribution of participants could be found in Table 1. For participants on the 9th floor, they walked into the stairs when received a signal of ''Ready, Go!'', and for the rest of participants on the 7th floor, 5th floor and 3rd floor, they began to walk into the corresponding stairs when they saw the participants above reached the floor-stair interface of their floors.

3. Results and discussion

Detailed movement data was extracted for the entire evacuating population. This was derived from the video footage collected from both of the evacuation scenarios. For example, as shown in Fig. 2, the times of the participant with the number 24 on his hat entered and left the specific floor could be recorded manually. Similarly, we extracted the times that all participants entered and left the specific floors during the two evacuation scenarios. The detailed analysis of pedestrian movement characteristics down stairs is presented in the following subsections.

3.1. Phased evacuation process

Phased evacuation refers to the situation where occupants who are located on a dangerous floor are evacuated initially, and