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Experimental study on small group behavior and crowd dynamics in a tall office building evacuation

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HIGHLIGHTS

- Experiments considering different social relations are conducted in a tall office building.
- Space-time features, speed characteristics and density-speed relations for each experiment are analyzed.
- Speed discrepancies for each pair and impacts of small groups on flow are discussed.
- Small groups make positive or negative impacts on crowd dynamics with depending on the competitive mechanism.

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ABSTRACT

It is well known that a large percentage of occupants in a building are evacuated together with their friends, families, and officemates, especially in China. Small group behaviors are therefore critical for crowd movement. This paper aims to study the crowd dynamic considering different social relations and the impacts of small groups on crowd dynamics in emergency evacuation. Three experiments are conducted in an 11-storey office building. In the first two experiments, all participants are classmates and know each other well. They are evacuated as individuals or pairs. In the third experiment, social relations among the participants are complex. Participants consist of 8 families, 6 lovers and several individuals. Space–time features, speed characteristics and density–speed relations for each experiment are analyzed and compared. Results conclude that small group behaviors can make positive impacts on crowd dynamics when evacuees know each other and are cooperative. This conclusion is also testified by four verified experiments. In the third experiment, speeds of evacuees are lowest. Small groups form automatically with the presence of intimate social relations. Small groups in this experiment slow down the average speed of the crowd and make disturbance on the crowd flow. Small groups in this case make negative impacts on the movement of the crowd. It is because that evacuees do not know each other and they are competitive to each other. Characteristics of different types of small groups are also investigated. Experimental data can provide foundational parameters for evacuation model development and are helpful for building designers.

1. Introduction

Collective behavior and evacuation dynamics have been investigated for several decades. As we have known, crowd motion is driven by the interaction between occupants and surrounding during evacuation. Crowd consists of not only

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individuals but also occupants in groups [1]. Research has found that up to 70% of people in the crowd are actually moving in group under normal condition [2]. A group exists in form of lovers, friends, families and so on, which often have two to four members. Cohesion between groups' members is so strong that members intend to stay together even in emergency [3]. It is quite common in office and residential buildings as well as shopping malls during evacuation. For example, according to survey, more than 85% people form groups with others during the "9.11" WTC disaster and most of the them come from the same or adjacent office [4]. Obviously, the relationship may influence the behavior of the members of group, such as competition and cooperation behaviors during evacuation [5]. Furthermore, the groups may also affect people around them since the groups may become obstacle for the surrounding people during evacuation and finally affect the pattern and movement of the whole crowd [6,7]. It can be concluded that the presence of different social relations and various types of the groups may make a big difference to the characteristics of crowd dynamics.

Pedestrian group behaviors have been investigated by the experts in different research areas, such as, sociology, physics, and mathematics. Experiments and simulations are both performed. Experimental studies mainly focus on the groups' movement characteristics [2,8,9] and affected factors on them [10–12] in normal condition as well as decision-making behaviors [13]. Very limited studies focus on small groups' behaviors, moving speeds, and their impacts on crowd flow in emergency. Simulation studies focus on developing or improving pedestrian models by considering group effect. Social force model [2,14,15], field floor model [16,17] and agent-based model [18–22] are among widely employed models. They have been modified and extended to study group behaviors and their impacts on crowd movements. Even though simulation researches have carried out on this topic for relative simple scenarios in normal and in emergency, the parameters used in the model should be verified and analyzed. Experiments considering various groups in different scenarios should be investigated.

Stair, as an essential exit in the building, plays an important role in emergency evacuation. Evacuation using the stairs is more complex than evacuation in the rooms or corridors. It is significant to study evacuation in staircase. Crowd dynamic parameters and factors which affect evacuation efficiency and human behaviors have been discussed. Fruin et al. [23], Proulx [24], Peacock et al. [25,26], Fang et al. [27], and Kuligowski [28] studied movement characteristics of pedestrians and concluded that a series of movement speed ranges were possible in the different staircase evacuation scenarios. These data provided the foundation for future code development. They also suggested that motion characteristics of evacuees depend on many factors, like gender, age. Song, Huo and Ma et al. [29,30] particularly investigated the speed and time features along with transit behaviors in an high-rise building evacuation and it was found that overtaking phenomena were observed frequently on the refuge floor. Fujiyama [31] developed a model to predict the walking speed of pedestrians in the staircase. Parameters such as building layout, physical conditions of the occupants, and numbers of the exits all make significant impacts on evacuation efficiency. Pauls et al. [32] explored the minimum stair width for evacuation. A series of width are listed for different types of stairs. Gwynne et al. [33] and Qu et al. [34] simulated the movement of pedestrian on the stairs. They pointed out that staircase geometries such as the number of steps and the depth of treads affect the movement of the evacuees. Lee et al. [35] conducted evacuation experiments under different widths of corridors and stairs. It was concluded that evacuation behaviors were mainly influenced by the locations of the stairs. Lei et al. [36] observed a dormitory evacuation and used FDS+Evac software to discuss the width of the stair and the exit on flow rates, it was founded the existence of stairs caused flow stratification, and the larger the exit width, the earlier the stratification phenomenon appeared. Galea et al. [37] and Boyce et al. [38], investigated how various factors, such as stair widths, population characteristics and geometrical locations of the floor, influenced merging behavior. Ding et al. [39] simulated stair evacuation with the improved cellular automata model, evacuees' walk preference behavior is considered in the model. Yang et al. observed [40] small groups behaviors during staircase evacuation, but only their impacts on crowd flow are mentioned. Even though staircase evacuation has been investigated widely, social relations and small group behaviors are barely considered.

This paper aims to study the crowd dynamic considering different social relations and the impacts of small groups on crowd dynamics in the staircase experiments. Crowds consist of individuals, pairs and a mixture of individuals and small groups respectively. The article is organized as follows. Section 2 introduces the experiment setup and method. Sections 3 and 4 presents the detailed results of experiments and discussion. Lastly Section 5 is the summary of our work.

2. Experimental setup and method

2.1. Building layout

Controlled experiments in our study are conducted in an 11-storey office building in Tsinghua University in China. All evacuation experiments start on the tenth floor in the building, whose layout is presented in Fig. 1. There are two staircases and two elevators in the building. However, only Stair 1 is used in the experiments. The structure and dimension of Stair 1 is shown in Fig. 2. It is 1.2 m wide while each step is 0.15 m high and 0.3 m deep. Step numbers in each floor are different. There are 25 steps in each floor from floor three to floor ten while 35 steps in floor two. It is noted that floor one is the ground floor. The travel distance between each floor can be formulized as follows [27]:

$$L = n_s l_{inclination} + (n_f - 1) l_{turning}, \tag{1}$$