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Modeling the emergency evacuation of the high rise building based on the control volume model

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ABSTRACT

Safety evacuation is one of the major requirements in evaluating the fire safety performance and design of the high rise buildings. The main aim of this study is to simulate the dynamics of the evacuees and derive the evacuation times of the high rise building by using the control volume model. The control volume model assumes that each individual is an independent particle and a virtual closed surface that can be formed by connecting the waiting persons at exit. This model had been successfully used to simulate the dynamic change of the evacuation occupants of the mass rapid transit station. In this study, the evacuation simulation process is divided into five stages and based on the assumptions of homogeneous flow with merge flow ratio where the exit flows from different floors meet and merge together. Seven scenarios are analyzed by using the various values of the parameters which influenced the evacuation process in the high rise building including walking speed, coefficient of flow rate and merge flow ratio. The simulation results are found to be in good agreement with the results of NFPA method. Furthermore, the dynamic characteristics of the evacuation process at each time-step for each of the floors are presented and discussed.

1. Introduction

With the rapid developments in performance-based fire engineering, many evacuation simulation models have been developed to analyze the performance of evacuation and used in fire safety design of buildings. One of the complicated problems of simulation model is the treatment of the human behaviors.

The simulation models are basically classified into two subsets: macroscopic and microscopic models (Zhong et al., 2008; Pelechano and Malkawi, 2008). The macroscopic models consider the evacuees as an integer with the same characteristics so that the evacuation performance depends on the crowd flow velocity, crowd density, and physical factors of architectures such as regression models (Milazzo et al., 1998), queuing models (Lovas, 1994), gas-kinetics models (Henderson, 1971), and Takahashi model (Takahashi et al., 1989), etc. The microscopic models not only consider the physical factors of architectures but also study the behavior and decisions of the individual and their interaction with the others in the crowd. Social forces (Helbing and Mulnr, 1995; Helbing et al., 2000), rule-based (Arentze and Timmermans, 2007), time-varying network (Lin et al., 2008), integrated network approach (Yuan et al., 2009), spatial-grid evacuation (SGEM) (Lo and Fang, 2000; Zhi et al., 2003; Lo et al., 2004; Lo et al., 2006), fine grid (Hu et al., 2013), hybrid space discretisation (Chooramun et al., 2012), finite stat automata (FSA) (Joo et al., 2013), and cellular automata models (Yang et al., 2005; Zhao et al., 2006; Song et al., 2006; Yuan and Tan, 2007; Zhao et al., 2008; Zheng et al., 2010; Chen et al., 2012; Song et al., 2013) are included in microscopic category. In addition, a large number of microscopic model tools for the analysis of the building evacuation have been developed such as EXITT (Levin, 1988), SIMULEX (Thompson and Marchant, 1995), and building EXODUS (Galea and Galparsoro, 1994; Gwynne et al., 2001).

Pelechano and Malkawi (2008), and Zheng et al. (2009) presented a review of crowd simulation models and discussed the advantages and disadvantages of these approaches. The combined approach for improving enclosure design on the evacuation modeling analysis had been developed by Tavares and Galea (2009). Recently, Nguyen et al. (2013) presented an agent-based evacuation model with smoke effect and blind evacuation strategy (SEBES) which respects that recommendation by integrating a model of smoke diffusion and its effect on the evacuee's visibility, speed, and evacuation strategy. Furthermore, a review of literature conducted on human behavior and modeling research for high-rise building evacuations was carried out by Ronchi and Nilsson (2013,

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2014), and they employed a combined use of vertical (stairs and elevators) and horizontal egress components (transfer floors and sky-bridges) to investigate the effectiveness of different evacuation strategies for high-rise buildings.

It is well known that stairwell is one of the most important emergency accesses in a high-rise building. The performance and efficiency of evacuation of a high-rise building are related to the life safety of occupants in emergency situations. In recent years, human behaviors are taken into consideration in designing simulation models to predict the time and method required for escape in a more rational method. Therefore, a lot of studies such as evacuation experiments, pedestrian moving surveys, and fire drills have been used to investigate the effect of human behaviors on evacuation process (Jiang et al., 2009; Jiang et al., 2010; Fang et al., 2012; Guo et al., 2012; Ma et al., 2012). In addition, evacuation dynamics is significantly affected by the building geometries and the evacuating population under consideration such as the presence of disabled occupants, counterflows, premovement delays, exit choices, and so on. In fact, people with sensory and mobility-related disabilities not only may need assistance to safely exit but also may block the evacuation of other people due to their slower speeds and larger space requirements, which results people with disabilities may not provide accurate estimates of proposed evacuation strategies (Koo et al., 2013).

In this study, the control volume model is used to simulate the resident evacuation of the high rise building. This model has been applied to evacuation time calculation in MRT stations and the results were proved quite reasonable by Wu et al. (2010). One of this basic assumptions of this model was adopted a hydraulic analogy which evacuees were considered as homogeneous fluid flow during the evacuation process. A number of parameters such as the exit flow rate, walking speed, coefficient of the exit flow rate, and merge flow ratio are also taken into consideration in the continuous flow equation to calculate the total evacuation times and the number of people stagnating in time scales.

Based on the control volume model and the scenario analysis of emergency evacuation, we have presented a novel approach to investigate and explore the process of occupant evacuation simulation via a 9-story office building built by NFPA. The results of evacuation time in this study agree well with the results of NFPA method (Fahy, 2008) when using the same walking speed, dimensions of the floor, and coefficient of the occupant flow rate, which verified the rationality of the control volume model in both modeling and execution aspects. The control volume model combines the merits of both macroscopic and microscopic theories. The concept of merge flow ratio is based on the assumption that the evacuees from different floors meet and merge together. By varying the values of walking speed, coefficient of flow rate, and merge flow ratio, the numerical results of the different cases of high rise building evacuation are simulated and obtained.

2. The assumptions in modeling high-rise building evacuation

2.1. Basic assumptions

In this paper, the control volume model theory is considered as a basis and referred to NFPA in the algorithm of evacuation time calculation. The physical assumptions of the control volume have been defined by Wu et al. (2010). When the occupants in the floor escape, they flow out from the rooms and tend to stagnate near the exit of the floor as shown in Fig. 1.

During evacuation process, when the evacuation occupant flow is larger than the capacity of the exit, a virtual closed surface (control surface) is formed by connecting the particles at the exit and that is changed with time. By setting the height of the particle (each individual) as 1, the area of the closed surface is equal to the control volume. Assuming the particle number per unit area as a constant, the transient area of the control volume can be easily derived from particle number within the control volume. The further assumptions of this model are shown as following:

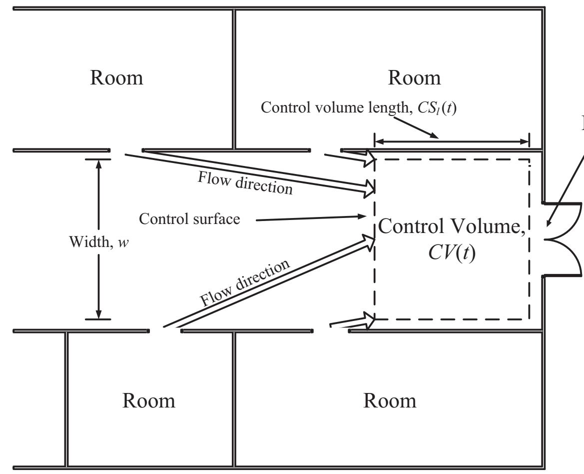

Fig. 1. The control volume model of the floor evacuation.

(1) During evacuation the evacuee flow is homogeneous, which means the evacuee walks with the same velocity, the evacuee flow from door or exit is continuous, the specific flow is a constant, and all occupants start egress at the same time.
(2) When stagnation occurs, the number of the occupants per unit area remains a constant.
(3) In each floor, the merge flow ratio of the descending stair entry flow and exit flow is a constant.
(4) The pre-movement time – lag, alarming response, and broad casting response are not considered.
(5) The occupant reaching the ground floor is considered a successful escape.

The total number of occupants flowing to the control volume at certain time point t can be presented as follows (Wu et al., 2010):

$$Q_{total}(t) = \sum_{n=1}^{M}\left(\dot{Q}_n(t) \times t\right) + TR - \dot{Q}_{out} \times t \tag{1}$$

where $\dot{Q}_n(t)$ is the flow rate of the occupants at the nth exit moving to the control volume (people/s), TR is the original number of occupants on the floor (people), t is the time scale (s), and $\dot{Q}_{out}$ is the flow rate of the occupants moving toward the exit (people/s). Because the number of occupants per unit area is constant, the size of the control volume at certain time point t can be formulated as $CV(t) = Q_{total}(t)/PA$ where $CV(t)$ is the value of the control volume at certain time point t (m^2), PA is the number of occupants accommodated per unit area (people/m^2).

The length $CS_l(t)$ of the control volume at certain time point t can be derived as:

$$CS_l(t) = CV(t)/w \tag{2}$$

where w is the effective width of the corridor (m). It is worth mentioning that the effective width of the corridor is not equal to its actual width as passengers tend to flock around the exits.

2.2. Scenario analysis of Emergency evacuation

The emergency evacuation is divided into five stages where stage 1 is the occupants departing from the room and arriving at the floor exit; stage 2 is the occupants descending to the next floor;