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Probabilistic model for safe evacuation under the effect of uncertain factors in fire

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ABSTRACT

As people's evacuation behavior in a building fire is uncertain, there are therefore many uncertain factors affect the people's evacuation process. In this study, Latin Hypercube Sampling method has been used to mathematically describe the determinacy and randomness in people's evacuation process. Further, a probabilistic model for people's safe evacuation has been developed. That is, Latin Hypercube Sampling method has been used to carry out a computer simulation sampling for the uncertain factors in the evacuation process, in which a probability density function has been used to describe the randomness of the uncertain factors in the evacuation process. In this way, the expected probability distribution of people's egress time has been determined. By comparing the mathematical expression of people's available safe egress time (ASET) with that of the people's required safe egress time (RSET), the probability distributions of evacuation safety with its margin have been predicted under the effect of uncertain factors in evacuation process. The probability model developed in this study is more reasonable than the traditional deterministic evaluation method for people's safe evacuation, and it is more suitable for the evaluation of risk in a building fire where people with relatively large mobility and irregular distribution.

1. Introduction

Evacuating people safely in a fire is a process in which people are evacuated to safe zones when there is a fire. In current research, two parameters are generally used to determine whether people can be evacuated safely, i.e., the available safe egress time (ASET) and the required safe egress time (RSET) Kuligowski, 2013. If ASET is more than RSET, it means that people can be evacuated safely from the building to the safe zones. The parameter ASET is the duration from the start of a fire to such a disastrous fire environment in which people can no longer be evacuated. It is also the duration from the start of a fire to the time when the hazard factors in a fire can endanger the evacuation. The ASET can be determined by fire model or field simulation (Ronchi, 2013).

The parameter RSET is the time required for people to evacuate to safe zones after the occurrence of a fire, which includes the recognition time, pre-movement time and movement time. These three times are explained as follows. (1) Recognition time. An detector signal is generated when the fire detector installation is activated by the release of hot smoke or thermal radiation in case of fire. Then, people or evacuees themselves realize the occurrence of fire. This period is called the recognition time, whose duration depends on the type and layout of the detector installation, scale of fire and its growth rate. Society of Fire Protection Engineers (SFPE) has summarized the models which can predict the recognition time. They have further developed corresponding prediction models of the recognition time for stable and instable fires (Seguridad contra incendios et al., 2002). (2) Pre-movement time. The pre-movement time in an evacuation is closely related with their psychological state, behavior characteristics, age, and degree of familiarity with the buildings, sensitivity to react, and even evacuees' cluster characteristics. All these factors have a great deal of randomness. Hence, it is difficult to use mathematical functions to describe the pre-movement time accurately. Two approaches are currently used to carry out research on people's pre-movement time, i.e. simulation modeling and evacuation testing. For example, Gwynne et al. developed a behavior process model to simulate people's recognition of fire, decision making and preparing for evacuation (Gwynne et al., 2001). (3) Movement time. The movement time is the time required for all the evacuees

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to evacuate to safe zones from the beginning of evacuation action. This period depends on the evacuation parameters such as people density, maximum indoor evacuation distance, effective width of evacuation door, and specific flow (Zhang et al., 2016). Until now, some evacuation simulation models, such as BGRAF, EXODUS, SIMULEX can be used to predict the movement time and performance of evacuations in a specific building and thus they become an important tool for doing the building evacuation analysis. In recent years, Kuligowski has classified 28 different egress models based on the level of complexity in occupant behavior (Kuligowski, 2004). Santos and Aguirre have described a critical review of emergency evacuation simulation models from the simulation methods including flow-based, cellular automata, and agent-based models (Santos and Aguirre, 2004). Tang has developed an agent-based simulation model which incorporates the fire scene and the building geometry by using a fire dynamics simulator (FDS) based on the computational fluid dynamics and geographic information system (GIS) data to model the occupant response (Tang and Ren, 2008). Braglia has proposed a new game theory based approach for the evacuees' exit selection in emergency conditions. The model involves many other parameters and aspects attempting to obtain a satisfactory representation of the actual evacuation process and the human behavior in emergency conditions (Braglia et al., 2013).

However, in a real fire, people's evacuation behavior is characterized by typical uncertainty features under the interaction of the fire source, people and building. For example, during the evacuation process, there can be congestion around the evacuation exit. Hence, there is uncertainty in the available exit width for evacuation before fire. Therefore, duality exists in the evacuation process, which includes determinacy and randomness (Magnusson et al., 1996). Current research on people's safe evacuation in a thermal environment of buildings still uses the deterministic approach, while there is little research on the uncertainty and randomness of the evacuation parameters. Maclennan et al. suggested that the Weibull distribution can be used to model the probability distribution of RSET (Maclennan et al., 1999). Francisco et al. analyzed many uncertainty parameters associated with the time prediction model of a heat detector. They then utilized a probability density function to describe the uncertainty parameters, thereby developing a preliminary probabilistic analytical model on the detection time (Francisco et al., 2005). Fruin showed that the uncertainty in people's body sizes plays a significant role in the accuracy of people's movement time (Fruin, 1971). Helbing et al. used certain distribution to model the uncertainty in the people's body size, thereby improving the computational accuracy and reliability of RSET (Helbing et al., 1997). However, there are few studies on the probability of people's safe evacuation based on the effect of uncertain factors in an evacuation process.

With respect to the uncertainty in RSET, research has been carried out in this study on the randomness and determinacy in the recognition time, people's pre-movement time and movement time. The mathematical expressions of determinacy and randomness in the evacuation process have been developed. Further, based on Latin Hypercube Sampling method, the probabilistic model for people's safe evacuation under the effect of uncertain factors in a fire has also been developed.

2. Mathematical expressions for determinacy and randomness in the evacuation process

2.1. Mathematical expression of people's evacuation process

The required safe egress time (RSET) consists of five parts: time from fire ignition to detection, time from detection to notification of occupants of a fire emergency, time from notification until occupants decide to take action, time from decision to take action until evacuation commences and time from the start of evacuation until it is completed. Time from fire ignition to detection and time from detection to notification of occupants of a fire emergency could be collectively referred to as "recognition time". While time from notification until occupants decide to take action and time from decision to take action until evacuation commences could be collectively referred to as "people's pre-movement time". Thus REST could be simplified as Eq. (1) shown in Fig. 1.

$$RSET = T_d + T_{pre} + T_t \tag{1}$$

where T_d is the recognition time (s), T_{pre} is the people's pre-movement time (s), T_t is time from the start of evacuation until it is completed (the people's movement time) (s). As each component is affected by some uncertain factors, RSET therefore follows certain probability distribution. The following is a discussion of the uncertain factors and its distribution function.

2.1.1. Recognition time

When a fire develops to a certain stage and heat or smoke is released by the fire source, a detector signal is generated when the fire detector installation is activated. Then, people realize there is a fire in the building. This period is called the recognition time. Due to the differences in the detector implementation, the recognition time is difficult to determine. Currently, the research on the uncertainty of the recognition time is mainly based on the mathematical statistical analysis.

As we all know, the smoke detectors are most widely used in the buildings. Beyler (1986) and Cleary et al. (2000) made lots research on the recognition time about spot-type smoke detectors. They developed a mathematical expression for the recognition time as follow:

$$t = \frac{u^{\frac{3}{2}}(R/H)^{0.945}}{0.45A^{\frac{1}{2}}\alpha^{\frac{1}{2}}H^{\frac{1}{2}}}(0.188H + 0.313R) + \frac{0.954(H+R)}{A^{\frac{1}{3}}\alpha^{\frac{1}{3}}H^{\frac{1}{3}}} + 15.53u^{-0.8} \tag{2}$$

where $A = g/C_pT_\infty\rho_\infty$; g is the acceleration due to gravity (taken as 9.8 m/s^2 in general); C_p, T_∞ and ρ_∞ are specific heat, temperature and density of the air in the outdoor environment, respectively; H is the ceiling height of the building (m), which is a fixed value for a specific building; and α is the fire growth rate (kW/s^2). The fire growth rate, α, is related to the speed at which the fire develops, and its value is affected by the type of combustible, indoor structure, ventilation, air contact area and so on. Thus, it is an uncertain parameter. Holborn et al. (2004) conducted a statistical analysis on numerous fire data and found that the fire growth rate α follows the lognormal distribution LnN(−5.4, 1.9), and its value ranges from 0.0117 kW/s^2 to 0.1876 kW/s^2. Further, R is the radial distance between the detector and the centerline of fire source (m). Since the fire source is located between two detectors and follows the uniform distribution, R is deemed to also follow the uniform distribution. The parameter u is the speed of the ceiling smoke flowing through the detector (m/s). Research by Curtat M showed that u follows the uniform distribution U(0.09, 0.5) Curtat, 2000.

2.1.2. People's pre-movement time

The people's pre-movement time is affected by many factors, including the building structure, location of the fire source, characteristics of combustible, distribution of occupants in building, and the type of alarm system. Under certain circumstances (e.g. people are awake, have experienced a fire drill or are familiar with the alarm system), the pre-movement time may be only a few seconds. However, under other circumstances (e.g. people are asleep, not familiar with the alarm system or can't get help from the staff),