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Simulation study on the effect of pre-evacuation time and exit width on evacuation

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Abstract Occupant pre-evacuation time is often oversimplified into an explicit value in evacuation calculation. In fact, it is not an explicit value but a random variable following some kind of probability distribution. In order to analyze the importance of pre-evacuation time in evacuation calculation, GridFlow evacuation model is utilized to study the effect of pre-evacuation time on evacuation under different occupant densities and exit widths in a single room scenario. The evacuation time calculated by using normal pre-evacuation distribution is compared with that calculated by explicit pre-evacuation time. Two faults are presented when pre-evacuation time is considered as an explicit value. The theory of congestion and queue is presented to analyze the calculation results. Moreover, this paper also presents probability distribution of the total evacuation time when the pre-evacuation time follows normal distribution. The results show that the evacuation time is dominated by pre-evacuation time and hardly dependent on occupant density when the mean pre-evacuation time is long. For long mean pre-evacuation time, low occupant density or wide exit, when pre-evacuation time follows normal distribution, the total evacuation time also follows normal distribution.

Keywords: fire, pre-evacuation time, evacuation, normal distribution, exit width, occupant density.

In fire risk assessment and performance-based fire protection design, a very important safety criterion is that occupants can evacuate to relative safety zones before onset of any potential hazards. At present, the required safe egress time (*RSET*) is generally thought to be less than the available safe egress time (*ASET*), namely

$$RSET < ASET. \tag{1}$$

ASET associates with many variables, such as the characteristics and disposition of the fire load, potential ignition sources, the reaction to fire properties of the lining materials and contents, the height and ventilation of the compartment and the nature of the fire effluent. *RSET* associates with fire detection and alarm, human behaviors in fire and building characteristics, etc. which can be classified into four parts

$$RSET = t_{de} + t_{alarm} + t_{pre} + t_{move}, \tag{2}$$

where t_{de} is fire detection time from ignition to detection; t_{alarm} is fire alarm time from detection to warning occupants to evacuate; t_{pre} is occupant pre-evacuation time defined as time interval between the warning of fire and the move towards an exit; t_{move} is occupant movement time required for occupants to reach a safe place.

Fire detection and alarm time are dominated by fire detection and alarm characteristics. Occupant pre-evacuation time is dependent upon such key features as occupancy type, warnings, occupant characteristics, building complexity and fire safety management strategy. Occupant movement time relates to occupant density, occupant evacuation velocity, building environment, etc. In terms of the overall evacuation, we need not consider fire detection time and alarm time which are explicit for a given scenario in any further detail here. Hence, occupant evacuation time t_{ev} is the sum of pre-evacuation time and movement time. Eq. (2) is transformed into

$$t_{ev} = t_{pre} + t_{move}. \tag{3}$$

For RSET calculation, travel time and physical movement through the escape routes were the research emphases in recent years[1−5]. For pre-evacuation phase, human behavior after people were aware of fire were usually studied using the data from real fire incident reports and evacuation drill without preannounce in different buildings[6−10]. However, few studies were explored on the effect of pre-evacuation time on evacuation. Occupant pre-evacuation time is often oversimplified into an explicit value in fire risk assessment and performance-based fire protection design. In fact, occupant pre-evacuation time is not an explicit value but a random variable following some kind of probability distribution. MacLennan *et al.*[11] suggested that Weibull distribution can be considered to be the most suitable which does not mean that there are no other suitable distributions. Purser *et al.*[12] suggested a unimodal, positively skewed distribution. For example, lognormal distribution would be suitable for most cases. Normal, log-normal and Weibull distributions can also be used to express pre-evacuation time[13]. In general, little is known of the pre-evacuation time probability distributions for different occupancies[14]. However, pre-evacuation time that follows probability density distribution has been validated. In order to obtain reasonable evacuation time for fire safety design, it is necessary to study the effect of pre-evacuation time on evacuation.

Occupant evacuation time is not a simple sum of pre-evacuation time and movement time, because these two components are dependent on each other. For example, one has a short pre-evacuation time, but he/she is far from an exit. Another one has a long pre-evacuation time, but he/she is near the exit. The evacuation time of the person who has a short pre-evacuation time may be longer than that of the person who has a long pre-evacuation time. However, if pre-evacuation time is characterized by an explicit value, the occupants will start evacuating at the same time. Evacuation time is only the simple sum of pre-evacuation time and movement time, which cannot reflect the real condition.

The purpose of this paper is to study the effect of pre-evacuation time on evacuation time and the probability distribution of evacuation time for different occupant densities and exit widths.

1 Simulation results and discussion

GridFlow evacuation model utilized in this paper was developed by Bensilum and Purser of BRE (Building Research Establishment). It was originally developed for research on human behavior and means of escape. The algorithms for movement and flow are described by Nelson and MacLennan in the SFPE Handbook[15]. Therefore, physical movement methods are similar to those used in other models such as Crisp, Exodus and Simulex. GridFlow differs from other models in that pre-evacuation time and pre-evacuation-travel interactions are considered in evacuation time modeling. In this evacuation model, pre-evacuation time can be characterized as an explicit value or probability distribution.

It is not possible to obtain every occupant's pre-evacuation time and location, because both of them are stochastic parameters. In order to design a scenario that can reflect the reality, occupants can be treated as a whole to distribute in the building at random under a given pre-evacuation distribution. We think it is appropriate in the statistical viewpoint. In this paper, normal distribution is employed to define pre-evacuation time.

1.1 The effect of pre-evacuation time and occupant density on evacuation

As room is the basic component of buildings, a single room scenario is considered. The dimension of the single room is 20 m×20 m with a 1m wide door opening, along the center of one wall. Five occupancy densities, 0.1, 0.2, 0.5, 1.0 and 1.3 ppl/m^2, are considered (ppl stands for people). Since the room floor area is 400 m^2, the corresponding number of people is 40, 80, 120, 200, 400 and 520 people. Walking speeds are assigned from a theoretical normal distribution (mean of 1.19 m/s and a standard deviation of 0.3 m/s)[15]. Mean values and standard deviations of pre-evacuation distributions are different in single enclosures and multi-enclosure buildings. In order to study the effect of different pre-evacuation distributions on evacuation, the mean values of occupant pre-evacuation distributions are considered as 30, 60, 120, 180, 240, 360 and 480 s. By eq. (3), because fire detection and alarm time are not considered, pre-evacuation time will begin at about 0. The probability of normal stochastic variables in interval $[\mu - 3\sigma, \mu + 3\sigma]$ is 0.9774 which indicates that the variables will almost be located in the interval. Therefore, the corresponding standard deviations are considered as about one-third of the mean values, namely 10, 20, 40, 60, 80, 120 and 150 s.

Fig. 1 shows the evacuation time calculated by normal and lognormal pre-evacuation distributions for 0.5 ppl/m^2 and 1.0 ppl/m^2. The results on the two distributions do not vary considerably for any given mean pre-evacuation time.

Fig. 2 shows the simulated evacuation times plotted as a function of mean pre-evacuation time and occupant density under normal pre-evacuation distribution.

Fig. 2 demonstrates that for the same occupant density, the longer the mean pre-evacuation time is, the longer the evacuation time will be. For the same mean pre-evacuation time, the evacuation time increases with the increasing occupant density. For a given exit width, higher occupant density may induce congestion and queue which will block people and prolong their evacuation time. When occupant mean pre-evacuation time is short, the evacuation time is affected by occupant density. However, the evacuation time becomes less dependent upon occupant density with the increas-

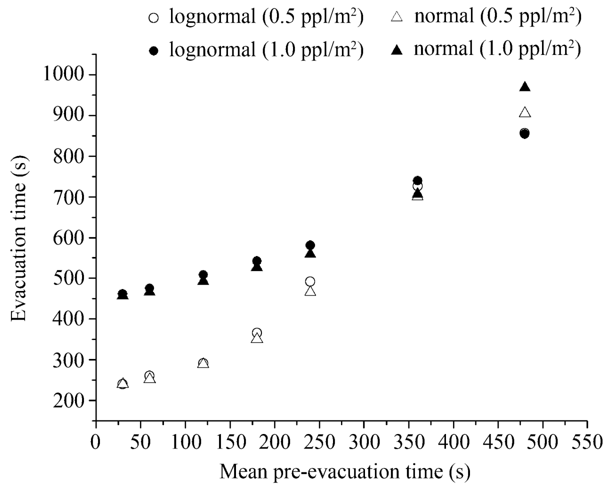

Fig. 1. Evacuation times calculated by normal and lognormal pre-evacuation distributions.

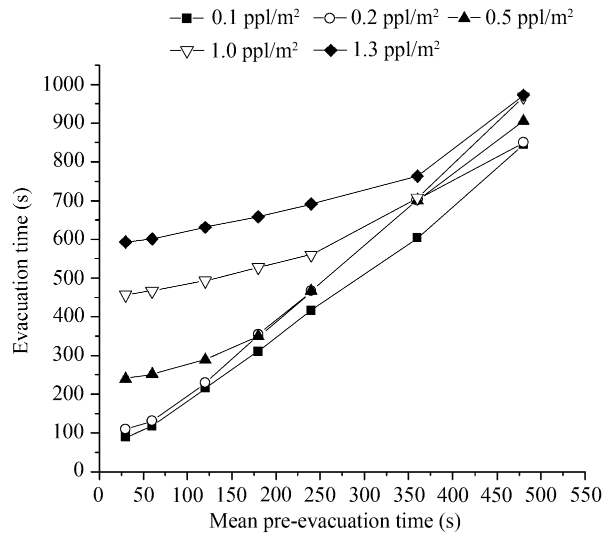

Fig. 2. Evacuation times calculated by normal pre-evacuation distribution for different occupant densities.

ing mean pre-evacuation time. For a given occupant density, people will start evacuating at different time with the increasing mean pre-evacuation time, which will reduce the level of congestion and queue around the exit. Therefore, occupant evacuation time will be dominated by pre-evacuation time and has little relationship with occupant density.

The above analysis shows that for a given exit width, when the mean pre-evacuation time is short, occupant evacuation time is a function of pre-evacuation time and occupant density. When the mean pre-evacuation time is long, occupant evacuation time is a function of pre-evacuation time with little relationship with occupant density.

1.2 The analysis of congestion and queue around exit

When mean pre-evacuation time is short, occupant evacuation time is a function of pre-evacuation time and occupant density. When mean pre-evacuation time is long, occupant evacuation time becomes less dependent upon occupant density. Such results are mainly caused by congestion and queue. Congestion and queue are likely to occur around exits when occupant density is high, thus slowing people's movement and prolonging the evacuation time. In this paper, in order to analyze the relationship of pre-evacuation time, occupant density and exit width, a differential equation is presented as follows:

$$dN = N_{\mathrm{all}} f(t)dt - n_{\mathrm{out}}dt, \quad (4)$$

where N_{all} is the total number of people in the building (ppl); $f(t)$ is the probability density function of occupant pre-evacuation time; n_{out} is the flow of evacuated people (ppl/s).

By introducing occupant density and integrating of eq. (4), the number of people in congestion and queue at time t can be obtained by

$$N_{\mathrm{cq}} = D_0 A F(t) - N_{\mathrm{out}}, \quad (5)$$

where N_{cq} is the number of people in congestion and queue (ppl); D_0 is occupant density (ppl/m^2); A is building floor area (m^2); $F(t)$ is the occupant pre-evacuation cumulative probability at time t; N_{out} is the number of evacuated people (ppl). In general, N_{out} is a variable controlled by exit characteristics.

If the mean value of probability density function $f_1(t)$ is larger than that of probability density function $f_2(t)$, for a given time t_0, $F_1(t_0) < F_2(t_0)$ can be easily obtained. That is, the shorter the mean pre-evacuation time, the larger occupant pre-evacuation probability. By eq. (5), for a given occupant density, an appropriate increase of the mean pre-evacuation time can reduce the level of congestion and queue. Moreover, the effect of pre-evacuation time and occupant density on evacuation can be analyzed from two extremes. First, when mean pre-evacuation time inclines to 0, namely people start evacuating simultaneously after hearing fire alarm, $F(t)$ inclines to 1. Congestion and queue will only be dominated by occupant density. Therefore, the total evacuation is affected by occupant density and travel time. Second, when mean pre-evacuation time inclines to ∞, $F(t)$ inclines to 0, so congestion and queue cannot form around exit. The total evacuation is dominated by pre-evacuation time irrespective of occupant density. When pre-evacuation time lies somewhere between these two extremes, then evacuation time is dominated by pre-evacuation time and occupant density.

By eq. (5), various exit widths will affect N_{out}. For a given occupant density and pre-evacuation time, N_{out} will increase with the increasing exit width. Then, N_{cq} will become smaller and evacuation time will become shorter. For a given occupant density, when mean pre-evacuation time inclines to 0, $F(t)$ inclines to 1. Exit width will have dominating influence upon congestion and queue. When mean pre-evacuation time inclines to ∞, $F(t)$ inclines to 0. Exit width will have little influence upon congestion and queue.

1.3 Comparison of evacuation times calculated by using normal pre-evacuation distributions and explicit values

When occupant pre-evacuation time is oversimplified into an explicit value, there will be two main faults.

First, the calculated evacuation time may be inaccurate. When occupant pre-evacuation time is defined as an explicit value, occupants will start evacuating at the same time. Serious congestion and queue that can affect occupant evacuation process will form around exits and corridors. However, since occupant pre-evacuation time follows some kind of probability distribution, people will start evacuating at different time. Such a serious congestion and queue will not form at all, so occupant evacuation time may become inaccurate when pre-evacuation time is defined as an explicit value.

Second, occupant evacuation cannot reflect the real evacuation process. Occupant pre-evacuation time is different for various buildings. For example, when occupants are distributed in multi-enclosure buildings, such as hotels or apartment blocks, there is likely to be a wide variation of pre-evacuation time. When occupants are all together in a single enclosure, such as a hall or a theatre, the range of pre-evacuation time tends to be similar[16]. Therefore, if occupant pre-evacuation time is characterized by an explicit value, the evacuation process cannot reflect the real evacuation process.

Fig. 3 shows the comparison of evacuation times calculated by using normal pre-evacuation distributions and maximum pre-evacuation times.

Fig. 3(a) demonstrates that for lower occupant densities (0.1 and 0.2 ppl/m^2) the differences are not very large. However, Fig. 3(b) demonstrates that for higher occupant densities (0.5, 1.0 and 1.3 ppl/m^2), the differences are more obvious. Moreover, the difference becomes larger with the increasing mean pre-evacuation time.

Fig. 3 can also be interpreted in terms of congestion and queue. For lower occupant densities, congestion and queue cannot form around the exit (Fig. 3(a)). Therefore, the difference is not very large. When the mean pre-evacuation time is short, because congestion and queue cannot be avoided for high occupant densities, the difference is not very large, too (Fig. 3(b)).

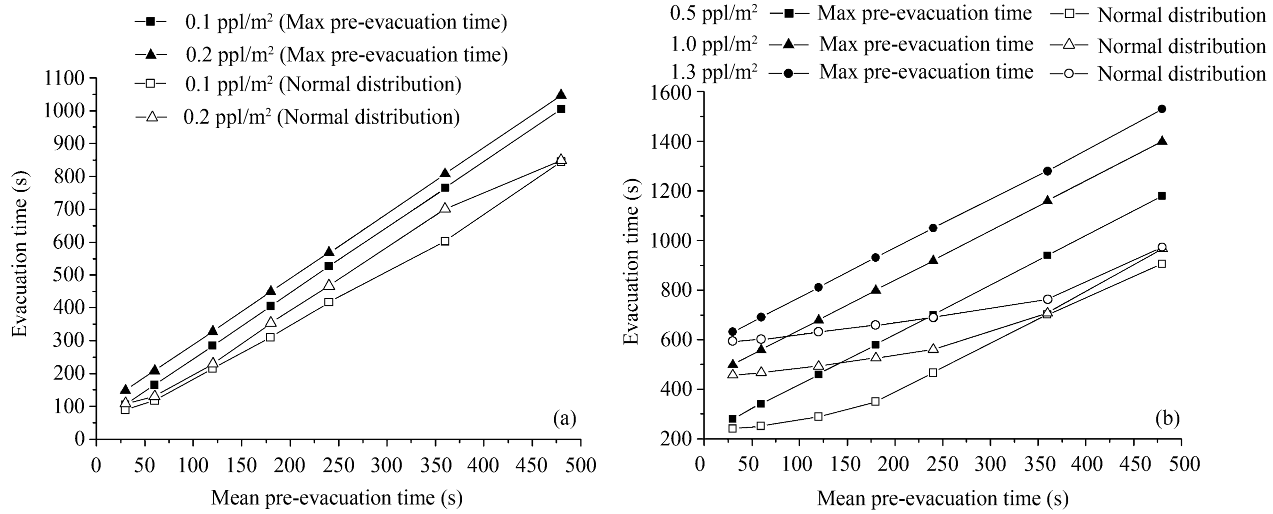

Fig. 3. Comparison of evacuation times calculated by using normal pre-evacuation distributions and maximum pre-evacuation times for: (a) 0.1 ppl/m^2 and 0.2 ppl/m^2; (b) 0.5 ppl/m^2, 1.0 ppl/m^2 and 1.3 ppl/m^2.

With an increase in the mean pre-evacuation time, according to eq. (5), occupants will start evacuating at a long distributed time, which will relax the congestion and queue. However, when occupant evacuation time is calculated by using maximum pre-evacuation time, people will start evacuating simultaneously. More serious congestion and queue will form around the exit, and then the difference becomes larger with the increasing mean pre-evacuation time.

1.4 The effect of exit width on evacuation

The above analyses about the effect of pre-evacuation time and occupant density on evacuation are for a one meter wide exit. By eq. (5), the exit width also can influence occupant evacuation time. Fig. 4 shows the variation of evacuation time with exit width when the mean pre-evacuation times are 60 and 180 s.

Fig. 4(a) demonstrates that the evacuation time becomes shorter with the increasing exit width. The evacuation time decreases sharply when exit width increases from 1 to 2 m. However, when exit width increases from 2 to 6 m, evacuation time becomes little dependent upon it. Moreover, the effect of exit width on evacuation time is more obvious for high occupant density than for low occupant density, which can be interpreted better in Fig. 4(b). For lower occupant densities, exit width has no effect on the evacuation times. For higher occupant densities, exit width has effect only on the evacuation times when exit width increases from 1 to 2 m. Fig. 4 also indicates that the evacuation time has an inclination to be independent of exit width with the increasing mean pre-evacuation time.

The above analysis can interpret the formation of congestion and queue. For lower occupant densities, congestion and queue hardly forms around the exit, so exit width has little effect on evacuation time. For higher occupant densities, congestion and queue will form around the exit. By eq. (5), N_{cq} becomes smaller with the increasing exit width, and then the evacuation time has a decreasing inclination. However, as exit width continues to increase, N_{cq} is zero or possibly negative meaning that congestion and queue cannot form. Because congestion and queue cannot form, evacuation time becomes independent of exit width. Moreover, $F(t)$ becomes smaller with the increasing mean pre-evacuation time. N_{cq} may be zero or possibly negative; therefore, evacuation time also becomes independent of exit width for a long mean pre-evacuation time.

1.5 The total evacuation time and its probability distribution

Fig. 5 shows the cumulative number of evacuated people against time for two occupant densities. Fig. 5 indicates that if each curve is parallel with others, queue will form around the exit. The flow of people through the exit is continuous. For a lower occupant density, wider exit or longer mean pre-evacuation time, the flow of people through the exit will become discontinuous.

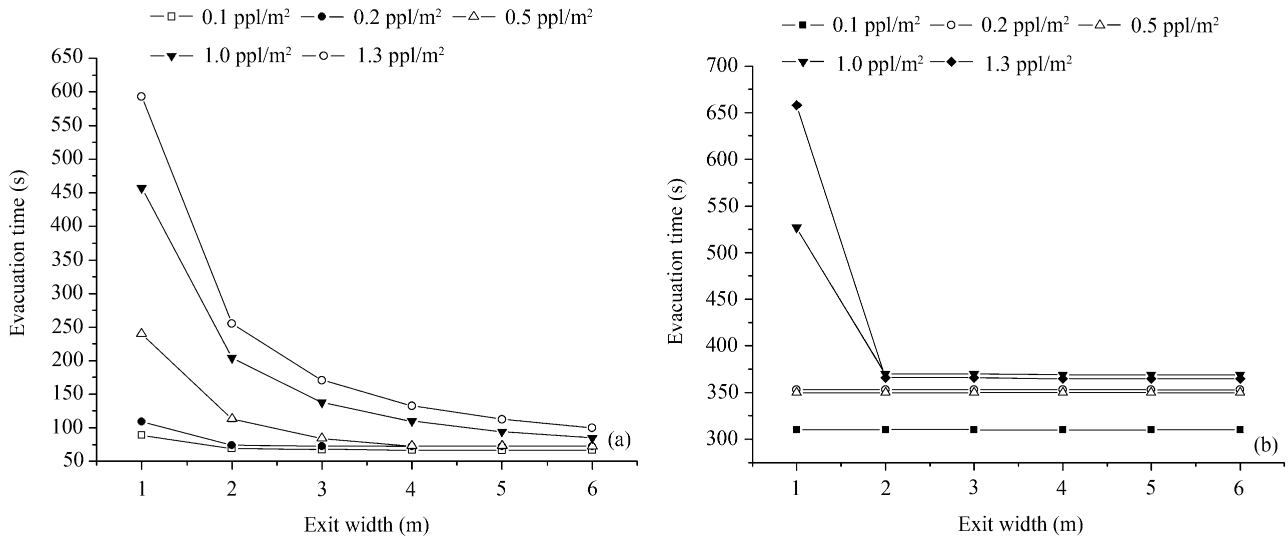

Fig. 4. Variation of evacuation time with exit width when mean pre-evacuation time is: (a) 60 s; (b) 180 s.

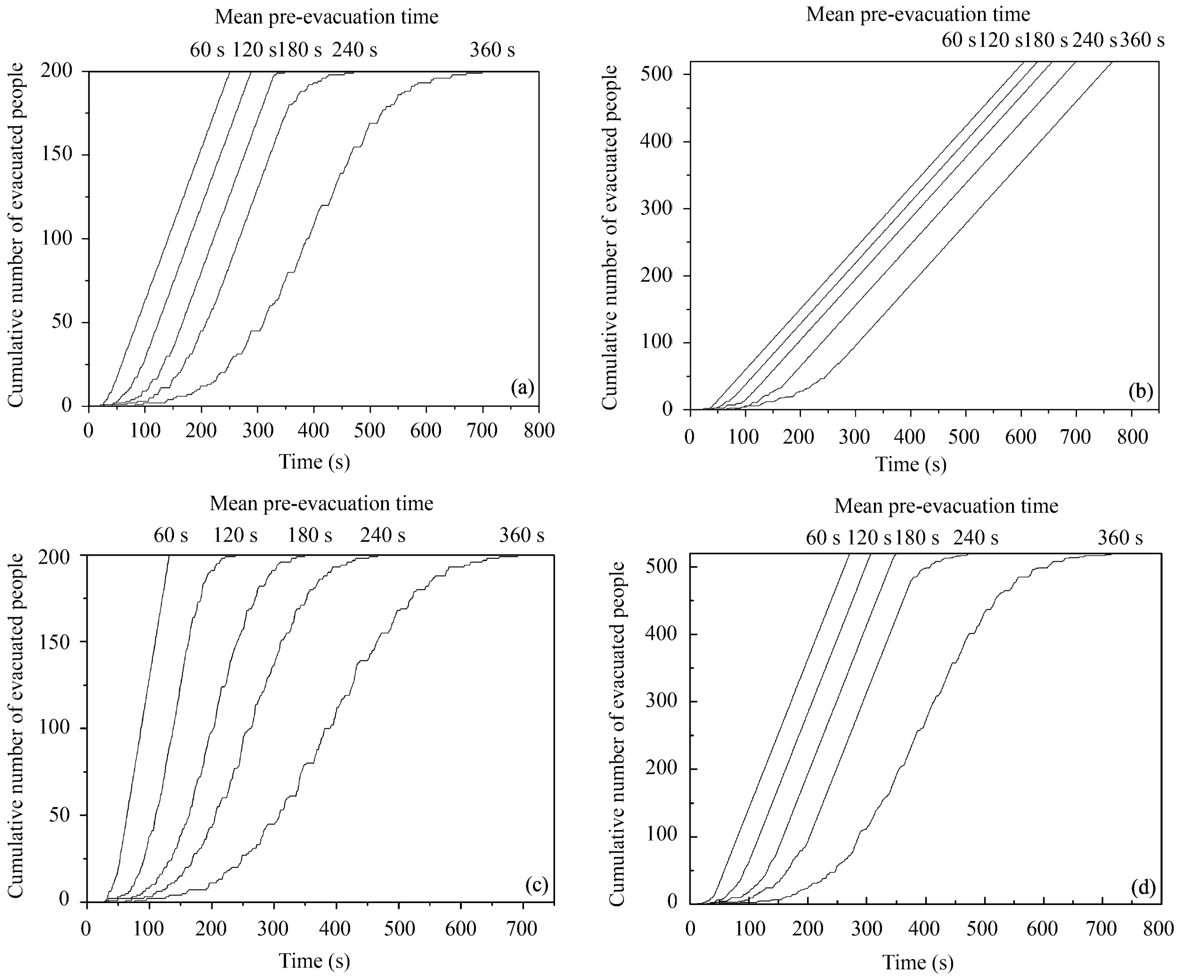

Fig. 5. The cumulative number of evacuated people against time when exit width is 1m for occupant density: (a) 0.5 ppl/m^2; (b) 1.3 ppl/m^2 and 2 m for occupant density; (c) 0.5 ppl/m^2; (d) 1.3 ppl/m^2.

Based on the data of Fig. 5(c) and Fig. 5(d), when the mean pre-evacuation times are 240 s and 360 s, probability density distribution and cumulative probability distribution of the total evacuation time are shown in Fig. 6.

Fig. 6(a) demonstrates that the theoretic normal curves of cumulative probability distributions agree with the simulation curves. Fig. 6(a) also shows that when the mean pre-evacuation time is 240 s, the mean value and the standard deviation of the total evacuation time distribution are 262 and 78 s, respectively. When the mean pre-evacuation time is 360 s, the mean value and the standard deviation of the total evacuation time distribution are 386 and 117 s, respectively. Fig. 6(b) also shows that the theoretic normal curves of cumulative probability distributions are in agreement with the simulation curves. When the mean pre-evacuation time is 240 s, the mean value and the standard deviation of the total evacuation time distribution are 274 and 80 s, respectively. When the mean pre-evacuation time is 360 s, the mean value and the standard deviation of the total evacuation time distribution are 393 and 115 s, respectively. These results indicate that when the pre-evacuation time follows normal distribution, and the flow of people through the exit is not blocked, the total evacuation time also follows normal distribution shifting to right by a constant.

Fig. 5(d) demonstrates that when the mean pre-evacuation time is short (60 or 120 s), congestion and queue form very quickly and the flow of people through the exit is blocked. Therefore, the total evacuation time will not follow normal distribution. When the mean pre-evacuation time is long (240 or 360 s), congestion and queue cannot occur. Even if there are con-

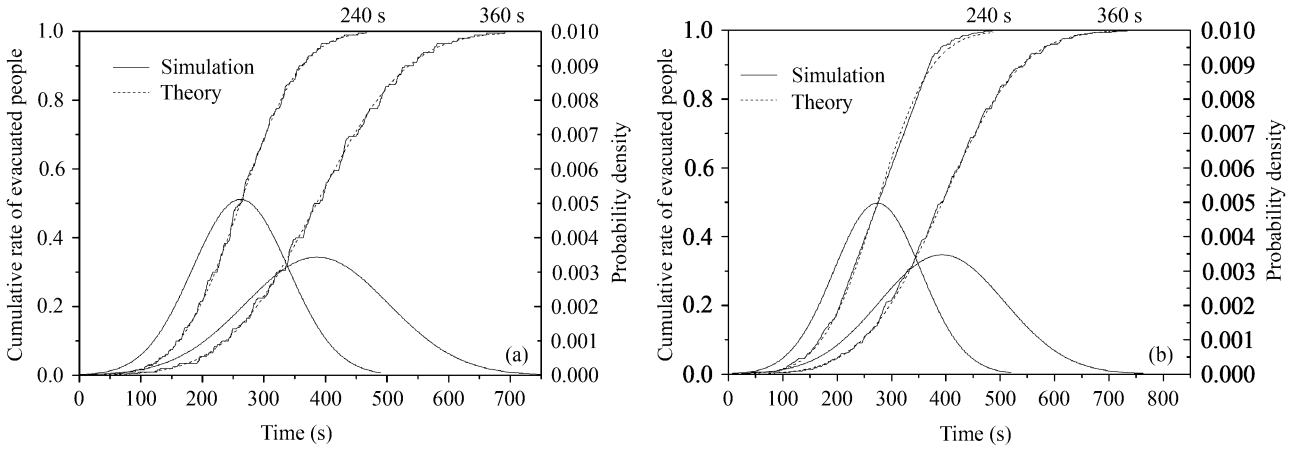

Fig. 6. The cumulative rate of evacuated people and probability density distribution of the total evacuation time when occupant density are: (a) 0.5 ppl/m^2; (b) 1.3 ppl/m^2 for the two-meter wide exit.

gestion and queue, it is only a temporary phenomenon which has little effect on evacuation. Therefore, the total evacuation time follows normal distribution.

2 Conclusions

In this study, the effect of pre-evacuation time and exit width on evacuation is studied by means of GridFlow evacuation model. The following conclusions can be drawn:

(1) Occupant evacuation time is a function of pre-evacuation time and occupant density. When the pre-evacuation distribution is small, evacuation time is mainly dominated by occupant density. When the pre-evacuation distribution is large, evacuation time becomes dominated by pre-evacuation time and has little relationship with occupant density. When occupants are all together in a single enclosure, such as a hall or a theatre, the range of pre-evacuation time tends to be similar. Therefore, occupant density in these buildings should be assessed accurately in fire risk assessment and performance-based design.

(2) When occupant pre-evacuation time is oversimplified into an explicit value, calculation results of occupant evacuation time may become inaccurate. For lower occupant densities, the differences between the evacuation times calculated by using normal distribution and maximum pre-evacuation time are not very large. For higher occupant densities, there are obvious differences between the evacuation times calculated by using normal distribution and maximum pre-evacuation time. Moreover, the differences become larger with the increasing pre-evacuation time. Therefore, when occupants are widely distributed in multi-enclosure buildings, a pre-evacuation time distribution is proposed for evacuation time calculation.

(3) When mean pre-evacuation time is short, evacuation time decreases sharply with exit width increasing from 1 to 2 m and gradually with exit width increasing from 2 to 6 m. When mean pre-evacuation time is long, for high occupant densities, evacuation time also decreases sharply with exit width increasing from 1 to 2 m. However, for low occupant density, evacuation time becomes little dependent upon it with the increasing exit width. Moreover, the effect of exit width on evacuation time is more obvious under high occupant densities.

(4) For long pre-evacuation times, low occupant densities, or wide exits, as long as congestion and queue cannot form, when pre-evacuation time follows normal distribution, the total evacuation time also follows normal distribution shifting to right by a constant.

In this paper, only simulation study on the effect of pre-evacuation time and exit width on evacuation is presented under different occupant densities. However, evacuation process is an extremely complex process. To validate simulation results, future work will be focused on collection of data from real fire incident reports and evacuation drill without preannounce.

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