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Influencing Factor Analysis of Ultra-tall Building Elevator Evacuation

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Abstract

This paper develops an elevator evacuation model for ultra-tall building which is implemented by AnyLogic package. Pedestrian movement and the elevator running can be well combined into the elevator evacuation model. Theoretical analysis is conducted to explore the influencing factors of the elevator evacuation and how the elevator evacuation time is determined by these influencing factors, including the number of occupants evacuating by one elevator, the height of refuge floor, the elevator speed and acceleration speed, the elevator capacity and elevator door width etc. Simulation experiments are conducted to analyze the elevator evacuation time of ultra-tall building. By theoretical and simulation analysis and the elevator evacuation time can be expressed as functions with several variables.

Keywords: ultra-tall building, elevator evacuation, influencing factor, evacuation time.

1. Introduction

As the population increases and valuable land becomes scare, large complex buildings are constructed in many large cities. Accidents such as fires and terrorist attacks that occurred in high-rise buildings caused enormous casualties and property loss. For instance, the terrorist attack \cite{1} when two commercial airliners crashed on the World Trade Center (WTC) Twin Towers on September 11, 2001 in New York, US, causing 2996 deaths, over 6000 injuries, and serious damage to numerous other buildings in the World Trade Center site. On November 15, 2010, an especially serious fire destroyed a 28-story high-rise apartment building in the city of Shanghai, China, killing at least 58 people and injuring more than 70 others \cite{2}. Some other serious accidents occurred over past few years. Therefore, studying the evacuation of ultra-tall buildings is important to reduce the deaths and property loss when emergency situations occur.

Elevators are not considered as a proper means of escape during fires, in accordance with the traditional prescriptive code of practice \cite{3,4}. Elevators are not designed for emergency egress in most existing buildings. People have been educated and trained to use stairways for fire escape. However, it is impossible to evacuate all occupants in an ultra-tall building in time with only stairs. If a certain ratio of occupants, especially children, the old and disabled, as well as pregnant women evacuate by elevators after they arrive at refuge floors, the total evacuation time may be reduced by half. In fact, elevator systems are employed for both normal and evacuation use in countries such as the United Kingdom, Australia, China, and the US \cite{5}. According to the International Building Code \cite{6} and Life Safety Code \cite{7}, passenger elevators complying with the requirements for general public use shall be permitted to be used for occupant self-evacuation. In a number of fire accidents over the past few years, elevators were used for successful fire escape \cite{8}.

In the recent years, a number of studies on elevator evacuation, including the calculation of elevator evacuation time \cite{9},
models of elevator evacuation [10,11,12,13,14,15,16,17,18,19,20,21], elevator planning strategies for evacuation [14, 22], and elevator protection in evacuation [15, 23, 24], have been conducted.

In most previous studies, an elevator serves many floors during emergency evacuation, which significantly reduces evacuation efficiency. Optimal evacuation time is proposed to be reached with an even higher percentage of elevator users on low floors than high floors [24] or the same percentage of elevator users on each refuge floor [25]. However, the optimal evacuation time may be not feasible in the emergency evacuation of ultra-tall buildings because: (1) in an actual evacuation of an ultra-tall building, occupants on high floors who have the most difficulty escaping by stairs and who need the aid of elevators the most are supposed to use the elevator in priority, such that the percentage of elevator users should increase with increasing refuge floor height; (2) in an evacuation of an ultra-tall building, occupants within the lowest stack zone are supposed to use the stairs rather than elevators for escape; and (3) elevators are unavailable on regular floors and are only available on refuge floors, which are always above 15th floor. With these considerations, an EE model is established in this research. This model comprehensively considers multiple influencing factors of elevator evacuation in ultra-tall buildings.

2. Elevator evacuation model

The detailed process of the elevator evacuation modelling refers to the chapter 4 of the PhD’s thesis [26]. This paper briefly introduces the modelling approach and focuses on the procedure of elevator evacuation and the analysis of the elevator running in the elevator evacuation.

2.1. Modeling approach

The elevator evacuation model is established with continuous space, discrete time and social force considerations, and implemented by a commercial package – AnyLogic in Java language. Pedestrian movements are implemented by AnyLogic Pedestrian Library package which enables pedestrian agents move in continuous space, reacting on different kinds of obstacles (walls, different kinds of areas) and other pedestrians. The elevator module is built on the basis of state chart provided by AnyLogic. Traditional flowchart frameworks suffer from the lack of scalability and are hardly reusable and they have been greatly improved in the AnyLogic.

2.2. Procedure of elevator evacuation

The procedure of elevator evacuation is presented in Fig. 1. From the evacuation procedure we can see that elevator evacuation includes two phases: elevator selecting; and elevator running. This paper focuses on the analysis of elevator running during the elevator evacuation of ultra-tall building.

![Elevator Selecting and Running Diagram](image)

When the elevator arrives at the refuge floor, occupants start to enter the elevator after the motor delay ($T_{Mo}$) and door...
opening \( (T_D^e) \). When the elevator is fully loaded \( (S_E = C) \), no more occupants can enter the elevator and the elevator starts to close door. The elevator starts to descend after the door closing \( (T_D^e) \) and motor delay \( (T_{MD}) \). It takes some time \( (T_{SL}) \) for elevator to arrive at the ground floor. Occupants start to walk out of the elevator after the motor delay \( (T_{MD}) \) and door opening \( (T_D) \). When all occupants are discharged from the elevator \( (S_E = 0) \), the elevator starts to close door. The elevator starts to ascend after the door closing \( (T_D) \) and motor delay \( (T_{MD}) \). The elevator comes back to the refuge floor after a period time of \( T_{SL} \). It is a round trip of an elevator which starts with arrival at the refuge floor and ends with returning to the refuge floor. It takes a period time of \( T_{RT} \) for the elevator to return to the refuge floor. Fig. 2 shows the process of the elevator evacuation in the elevator evacuation model developed in this paper.

![Elevator Evacuation Process](image)

(a) Waiting for elevator  
(b) Entering elevator  
(c) Elevator full  
(d) Elevator landing  
(e) Exiting elevator  
(f) Elevator empty

Fig. 2. Process of elevator evacuation in the elevator evacuation model

3. Influencing factor analysis

In this section, theoretical and simulation analysis are conducted to explore the influencing factors of elevator evacuation and how elevator evacuation time is determined by these factors. Detailed deducing process refers to chapter 5 of the PhD thesis [26].
3.1. Theoretical analysis

In the elevator evacuation model, it is assumed that the process of elevator ascending and descending is the same which includes three phases: acceleration phase; constant speed phase; and deceleration phase (see Fig. 3).

![Diagram of Velocity-time relationship of elevator](image)

Fig. 3. Velocity-time relationship of elevator

In the acceleration phase, the velocity of elevator can be expressed as

\[ V_a = aT \quad (1) \]

where
- \( V_a \) is the velocity of elevator in the acceleration phase;
- \( a \) is the acceleration speed;
- \( T \) is the time.

In the constant speed phase, the velocity of elevator stays a constant value \( V_m \) which is the maximum constant speed of the elevator. \( V_m \) can be expressed as

\[ V_m = aT_1 \quad (2) \]

where
- \( T_1 \) is the time when acceleration phase ends.

In the deceleration phase, the velocity of elevator can be expressed as

\[ V_d = V_m - a(T - T_2) \quad (3) \]

where
- \( V_d \) is the velocity of elevator in deceleration phase;
- \( T_2 \) is the time when constant phase ends.

Then the time for an elevator running a round trip between a refuge floor and ground floor can be expressed as

\[ T_{rt} = \frac{V_m}{a + H_k/V_m} \quad (4) \]
where

\( T_{ST} \) is the single trip time of elevator;

\( H_R \) is the height of refuge floor level.

Furthermore, the maximum constant speed cannot be more than a critical value \( V_M \)

\[
V_m < V_M = \sqrt{aH_R}
\]  

(5)

Besides the ascending and descending process, additional time is needed in the elevator evacuation for occupants entering and out of the elevator, elevator door opening and closing, motor delaying etc. With consideration to all those factors, one round trip time of an elevator in evacuation \( T_{RT} \) can be expressed as

\[
T_{RT} = 2T_{ST} + 4(T_{MD} + T_D) + T_{IN} + T_{OUT}
\]  

(6)

where

\( T_{MD} \) is the motor delay time of the elevator;

\( T_D \) is the time for elevator door opening or closing once;

\( T_{IN} \) is the time for occupants entering the elevator for one trip;

\( T_{OUT} \) is the time for occupants walking out of the elevator for one trip.

Combining formula 4.4 and 4.6, the elevator one round trip time can be expressed as,

\[
T_{RT} = 2\left(\frac{V_m}{a + H_R} + V_m\right) + 4(T_{MD} + T_D) + T_{IN} + T_{OUT}
\]  

(7)

The elevator evacuation time (\( T_E \)) is determined by the round trip time of elevator and the number of trips (\( n_t \)).

\[
T_E = n_t T_{RT}
\]  

(8)

The number of trips is related to the number of elevator users per elevator (\( N_{OE} \)) and elevator capacity (\( C \)).

\[
n_t = \frac{N_{OE}}{C}
\]  

(9)

Then the elevator evacuation time can be expressed as

\[
T_E = N_{OE} \left(2T_{ST} + 4T_{MD} + T_D\right)/C + 2 N_{OE} \left(\frac{Q_{ED}}{W_D}\right)
\]  

(10)

Where

\( T_{MD} \) is the motor delay, the door opening and closing delay;

\( Q_{ED} \) is the flow rate of elevator door when occupants coming in and out of the door;

\( W_D \) is the elevator door width.

3.2. Simulation analysis

Using the elevator evacuation model developed in this paper, simulation experiments are conducted to explore how the elevator evacuation time is determined by the influencing factors. In simulation settings are as follows and simulation results are presented in Fig. 4.

\( W_D \) (in meters): 1.5;

\( T_{ST} \) (in seconds): 15, 25, 35, 45, 50;

\( N_{OE} \) (in persons per elevator): 100, 200, 300, 400, 500, 600, 700;

\( C \) (in persons): 12, 15, 18, 21.
(a) \( \omega = 12 \)

(b) \( \omega = 15 \)

(c) \( \omega = 18 \)
By regression fit the elevator evacuation time can be expressed as
\[
T_e (1.5) = 2.105 N_{OE} T_{ST} / C + 4.776 N_{OE} / C^{0.23} + 0.45 T_{ST} + 57
\]  
(11)

4. Conclusion

In this paper, an elevator evacuation model is developed to explore which factors influence the elevator evacuation of an ultra-tall building and how the elevator evacuation time is determined by these factors. The main results are as follows:

1) By theoretical analysis, the main influencing factors of elevator evacuation include the number of occupants evacuating by one elevator, the height of refuge floor, the elevator speed, the elevator capacity, and the elevator door width etc. The elevator evacuation time can be expressed as
\[
T_e = \frac{N_{OE}}{C} \left( 2 T_{ST} + \frac{4 R_{CHE}}{N_{OE}} \right) + 2 \frac{N_{OE}}{C^{0.23}} + Q_{LAT} W_0 \]  
2) Using the elevator evacuation model, simulation experiments are conducted with the elevator door width 1.5 m, different elevator single trip time, elevator capacity and number of occupants evacuating by one elevator. By simulation analysis, the elevator evacuation time (elevator door width is 1.5 meter) can be expressed as
\[
T_e (1.5) = 2.105 N_{OE} T_{ST} / C + 4.776 N_{OE} / C^{0.23} + 0.45 T_{ST} + 57
\]

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