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Simulation Research on Fire Evacuation of Large Public Buildings Based on Building Information Modeling

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Abstract: Reasonable evacuation strategies are important in reducing casualties in the event of a fire. In this work, we conduct a simulation of a fire evacuation of a large public building based on the building information modeling technology to find the best evacuation strategy. We identify the tolerance limit of evacuees in case of a fire as the basis of the simulation using the fire dynamics simulator software. The following four evacuation strategies are proposed and simulated: stratified evacuation only by stairs, stratified evacuation mainly by stairs and supplemented by fire elevators, holistic evacuation only by stairs, and holistic evacuation mainly by stairs and supplemented by fire elevators. The case study of a college canteen shows that if 10% of evacuees (mainly elderly people who walk slowly and children who take up less space) are instructed to evacuate via fire elevators and the other 90% of evacuees (young men and women who move fast) use the stairs, the evacuation time can be reduced to a minimum. Some improvements in the design drawing result in the enhanced efficiency of the proposed strategy. The findings of this work are of great significance for the optimization of the structural design of large public buildings and provide some references for emergency evacuation.

Key words: Building Information Modeling (BIM); evacuation simulation; stairs-elevators combined evacuation model

1 Introduction

In the past decades, China has experienced rapid economic growth with an unprecedented increase in the number of large public buildings. However, in the event of a fire, the resulting high personnel density and complexity of such buildings may lead to irreparable property losses and casualties. The disadvantage of the traditional evacuation mode is that it takes a long time, it has low efficiency, and the corners of stairs can be easily blocked, resulting in secondary accidents. Therefore, the search for efficient evacuation strategies for pedestrians in large public buildings is crucial and has attracted the attention of numerous scholars.

The most significant feature of high-rise buildings is that they comprise several floors and people are evacuated vertically; hence, evacuation strategies supplemented with firefighting elevators§ can improve evacuation efficiency[1]. The topic of evacuation supplemented with fire elevators has long been studied. In the early 1980s, American scholar proposed that fire elevators could be used in emergency evacuations. Klote further discussed some fire elevator evacuation strategies, such as fire prevention, smoke prevention, and power supply for fire elevators and fire elevator shafts. In 1982,

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§ At present, ordinary elevators are not allowed to be used in fire incidents in China. Therefore, this work selects firefighting elevators as an evacuation aid tool.

he proposed a fire elevator emergency evacuation system, which marked the first case in which the fire elevator evacuation was considered as a system[2]. The research regarding fire elevators for evacuation has been growing since then.

The existing literature regarding the evacuation of large public buildings mainly focuses on three aspects, namely, evacuation model, evacuation route, and evacuation simulation. One of the first evacuation models is Helbing's lattice gas model, which can effectively identify the characteristics of a room to improve evacuation efficiency and room configuration[3]. Takimoto et al. proposed an improved agent-based cellular automaton model and analyzed the model by using average approximate field analysis methods and game theory[3]. Their results showed that adding obstacles before an exit could effectively solve exit obstruction. Ezaki et al. described the dynamic characteristics of pedestrians by using a regional model[4]. Their research showed that regional models are easier to use in simulating changes in building structure than the cellular automata model. Sheeba and Jayaparvathy proposed an evacuation scenario analysis model of fire accidents on the basis of stochastic Petri nets[5]. The relevant parameters of the model include panic between people, the safety of stairs, and the distance between each person and the floor exit[6]. To find the shortest evacuation time, Sticco et al. used the social force model in simulating crowd dynamics from the perspective of physics by considering three forces, namely, expected force, social force, and physical force[7].

Regarding evacuation routes, Mirahadi et al. used the VACUSAFE tool to find the safest egress route from each compartment and determine the most critical locations of fire initiation in a building for different fire scenarios[8]. Mirahadi et al. proposed a real-time path planning model to calculate the lowest risk path on the basis of the improved Dijkstra algorithm[8]. Jiang et al. modeled an evacuation space and path, constructed a Three-Dimensional (3D) dynamic escape model, and developed a virtual drill system with a 3D dynamic emergency response according to the characteristics of buildings and crowds[9]. Most studies on evacuation routes do not consider the behavioral attributes of personnel and completely obey the arrangement. In addition, the internal attributes of buildings are not accurate enough, and optimal paths need to be improved. Evacuation simulation has been favored by researchers because of its intelligence and accuracy.

Some commonly used evacuation simulation software includes Pathfinder, Exodus, and Simulex. Bourhim and Cherkaoui simulated the pre-evacuation response and behavior of people in emergency situations by using the commercial nature of virtual reality smart, providing material for emergency response training in high-rise residential fire evacuation[10]. Nguyen et al. considered important export parameters, such as crowd density and evacuation population demography, and used complex numerical simulation techniques to study a new method of emergency personnel exit[11]. Some studies have explored the evacuation of people in super high-rise buildings, but the influence of personal attributes on the efficiency of fire elevator evacuation has not been considered in the simulation process. Liao et al. regarded the feasibility of fire elevators for evacuation as the dynamics of evacuation systems[12]. Ma et al. proposed ultra-high-rise building evacuation with a fire elevator model that simulates human movement and fire elevator operation[13]. Ding et al. established evacuation model with a combination of stairs and fire elevators to evaluate the influence of the number of fire elevators and the maximum speed of fire elevators on evacuation[14]. Chen et al. proposed an elevator-assisted evacuation modeling method based on event-driven agent, which can not only capture the movement characteristics of people using stairs, but also the movement characteristics of elevators[15]. Ma et al. studied the number of evacuated persons, fire elevator operating speed, fire elevator capacity, and the proportion of persons evacuated via fire elevators by using a numerical simulation method[16]. By using Pathfinder, Ding et al. found that if the elderly and children take fire elevators first, the evacuation time could be reduced[14].

Although comprehensive studies have focused on emergency evacuation, several gaps remain. First, existing simulation models are mainly for plane evacuation and do not consider auxiliary evacuation tools, which are not applicable to vertical evacuation involving stairs and fire elevators. Second, the existing research about evacuation in large buildings does not consider the effect of evacuees' attributes on evacuation efficiency in the simulation process. Third, the interior design of large public buildings is very complicated, and existing models cannot accurately simulate building interiors.

With the development of building science, Building

Information Modeling (BIM) has become the main technology for achieving accurate modeling of the entire life cycle of a building. Given its advantages, BIM has also been used in many aspects of disaster prevention management. Cheng et al. evaluated different evacuation plans to improve evacuation performance by integrating BIM technology and the Agent-Based Model (ABM)[17]. Sun and Turkan developed a BIM-based simulation framework that implements the combination of Fire Dynamic Simulator (FDS) and ABM; the technology can simulate fire growth and evacuation performance for different building layout scenarios[18]. Hsieh et al. built a BIM-based intelligent system for fire prevention and disaster reduction, which can promote fire rescue and control by providing early detection and alarm, thereby improving holistic building safety and disaster response[19].

The contributions of the current work are as follows: First, we propose an evacuation strategy featuring a stair–elevator combination by considering the tolerance limit of evacuees in case of a fire. According to this consideration, we can then find the most efficient evacuation strategy. Second, we construct a 3D building model on the basis of BIM technology. The proposed model should ensure the consistency of the internal properties of an evacuated building with real-life conditions. The accuracy of simulation results can be improved using the proposed model. This work is expected to provide some decision bases for the evacuation of large public buildings.

The rest of this paper is organized as follows: In Section 2, we construct a BIM-based model by adopting a college canteen as a case. In Section 3, we further construct the FDS model. In Section 4, we provide the simulations on the basis of the built models. In Section 5, we simulate the stair–elevator combination strategy. In Section 6, we discuss the evacuation results. In Section 7, we propose some improvements in architectural design. In Section 8, we present our conclusions. Through this work, we hope to provide a basis for decision-making related to the fire evacuation of large public buildings and the optimization of building structural design.

2 Description of Research Object and BIM Model Construction

In this study, we choose a college canteen as a representative public building with high population density as our research object and apply it to the simulation of a scene of a fire evacuation. The building structure is a framed structure with three floors, a pile foundation, an area of 11 119 m^2, and a height of 15.3 m.

The first floor houses the dining room used by students and operation rooms. The second floor is equipped with halal operating rooms, offices, etc. The third floor is composed of various shops, private rooms, and so on. The first floor contains six exits, as shown in Fig. 1. Exit 1 is located at the northwest corner of the first floor. Exit 2 is next to exit 1 and traverses a narrow passage, which is relatively remote from staircase 1. Exit 3 is close to staircase 1, which can only go from the second floor to the first floor but not to the third floor. This exit is also far away from the other stairs (staircase 1, staircase 2, and so on) on the second floor. Exit 4 is close to staircase 2, which is an outdoor staircase. Exit 5 is far from exit 4 and other stairs. Exit 6 is located near an indoor staircase surrounded by narrow trails and is not easy to pass through. A fire elevator is situated next to staircase 1 and can be used by firefighters in case of a fire.

We adopt Revit software to build the BIM model, including the structural design and architectural design. Figure 2 shows the 3D model of the canteen drawn by the Revit modeling software according to the two-dimensional Computer Aided Design (CAD) drawings and other digital information.

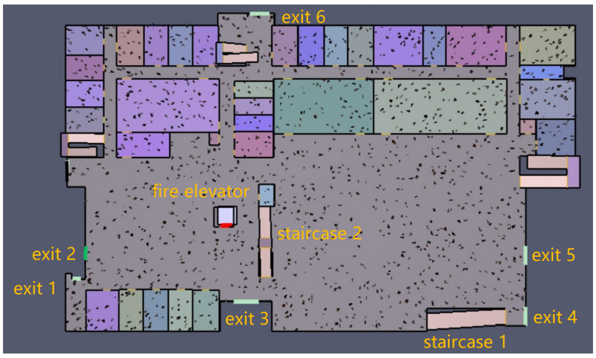

Fig. 1 Floor plan of canteen.

Fig. 2 BIM model of canteen.

3 Fire Dynamics Simulator Model Construction

3.1 Scene setting

Smoke temperature, CO concentration, and smoke visibility are important factors affecting personal safety in case of a fire. In this work, we adopt the FDS software to obtain the aforementioned parameters. For the college canteen adopted as the study object herein, we set the kitchen on the first floor as the fire point. In the event of a fire, the fire in the kitchen can spread to the second and third floors through the stairway. Smoke may also spread rapidly.

We assume that all smoke exhaust vents and other vents are working normally. The initial fire environment is set as follows:

(1) Initial ambient temperature: 23 ℃;

(2) Relative humidity: 50%;

(3) Fire type: Fast fire;

(4) Fire conditions: Smoke detector, temperature detector, thermocouple, and exhaust fan;

(5) Combustion type: Wood and composite materials;

(6) Fire scale: 6 MW;

(7) Smoke exhaust speed: 6 m/s;

(8) Air inlet speed: 3 m/s;

(9) Building height: 15.3 m;

(10) Run time: 600 s.

According to the design drawings of the canteen, four thermocouples, one smoke detector, and one temperature detector are installed on each floor. The position coordinates are as follows:

First floor:

Thermocouples (0, 0, 0); (−15, 25, 0); (15, −10, 0); (−10, −25, 0);

Smoke detector (−10, 0, 0);

Temperature detector (−5, −5, 0);

Second floor:

Thermocouples (0, 0, 5.1); (−10, 30, 5.1); (−10, −20, 5.1); (20, 10, 5.1);

Smoke detector (−10, 5, 5.1);

Temperature detector (0, −15, 5.1);

Third floor:

Thermocouples (0, 0, 10.2); (−10, 30, 10.2); (−10, −20, 10.2); (20, 10, 10.2);

Smoke detector (−10, 5, 10.2);

Temperature detector (0, −15, 10.2).

According to the modeling data, the ground elevation of the third floor is 10.2 m. Under the assumption that the normal height of an adult person is 1.7 m, the flue gas temperature, CO concentration, and smoke visibility 11.9 m away from the ground are taken as assessment indexes. The FDS model is shown in Fig. 3.

3.2 Operation results

According to the existing literature, the following conditions are required to ensure human safety in case of a fire:

(1) Smoke temperature: If the smoke temperature exceeds 180 ℃, then people will be at risk of burns during the evacuation process;

(2) CO concentration: When the volume percentage of CO reaches 1%, people will suffer from dizziness and chest tightness;

(3) Smoke visibility: Smoke visibility is generally determined by the building structure and area, and for large public buildings, it should not exceed 10 m.

By running the PyroSim software, which is a famous software for fire dynamic simulations, we obtain the 3D smoke view. The smoke distribution is shown in Fig. 4.

According to the simulation results, the temperature throughout the simulation is lower than 180 ℃ and should not cause harm to evacuees; in this case, we record t_1 as ∞. Then, 523 s after the fire, the CO concentration reaches 1%; we record t_2 as 523 s. Exactly 604 s after the fire, the flue gas visibility decreases to

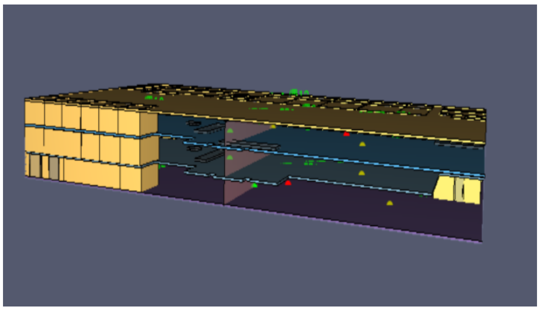

Fig. 3 FDS model.

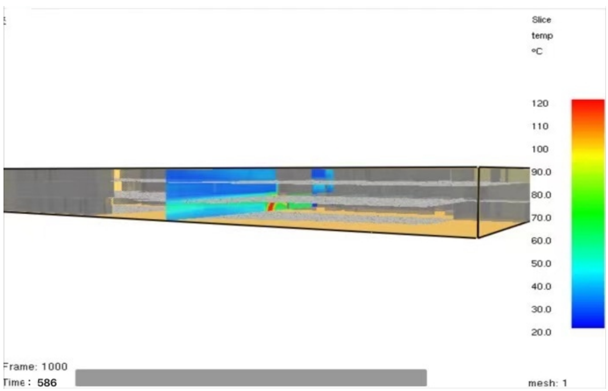

Fig. 4 Temperature distribution at 586 s.

10 m; we record t_3 as 604 s. Only when the tolerance limit is $\min\{t_1, t_2, t_3\} = \min\{\infty, 523, 604\} = 523$ s can the safety of evacuees be guaranteed. Therefore, the evacuation time of evacuees should not exceed 523 s; otherwise, their safety will be at risk.

4 Construction of Evacuation Simulation Model

4.1 BIM model conversion

In this work, we adopt the Pathfinder software to construct an evacuation simulation model, which is established after the BIM model. Given the incompatibility between Revit software and Pathfinder software, we need to convert the BIM model format, export the RVT format to DXF format, and import the DXF format into Pathfinder. To simulate the visibility of the process, we show in Fig. 5 the model after deletion and extraction.

4.2 Parameter setting

Some parameters in the evacuation, including the type of evacuees, walking speed, body width, and evacuation mode, need to be set reasonably.

4.2.1 Settings of evacuees

The number of evacuees is one of the basic parameters of evacuation simulation. We need to calculate the effective width of evacuation doors and safety exits on the basis of the number of evacuees in the building. The number of evacuees can be calculated according to the "Code for Fire Protection in Buildings Design" (GB 50016–2014) stipulated by the Chinese government. The calculation formula is the building area multiplied by the specified evacuees' density. Evacuees' density data are shown in Table 1.

According to the standard, the number of evacuees is 1.1 times the number of seats in case of the presence of fixed seats. According to the floor plan of the architectural design, each floor of the canteen is composed of rooms and halls. The number of evacuees in a room can be obtained by multiplying the building area by personnel density. Given the fixed number of seats in the hall, the number of evacuees in the hall is 1.1 times the number of fixed seats. The results are shown in Table 2.

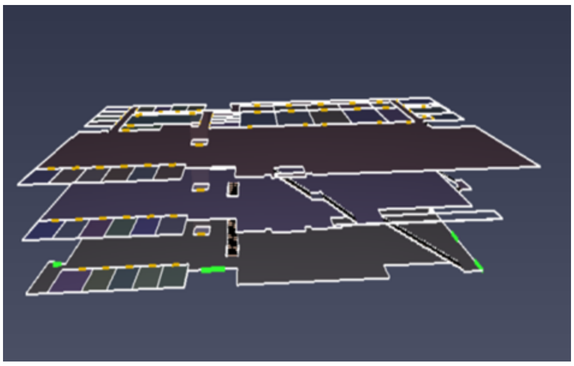

Fig. 5 Three-dimensional evacuation model after simplification.

Table 1 Evacuees' density data.

Floor	Evacuees' density
First floor underground	0.56
Second floor underground	0.60
First and second floors above ground	0.43–0.60
Third floor above ground	0.39–0.54
Fourth floor above ground	0.30–0.42

4.2.2 Evacuees' types and parameters

The evacuees in the college canteen are mainly diners (students and teachers) and staff. Our field research shows that some teachers and their children eat together in the canteen and that the staff mainly comprises older adults aged over 50 years. To simplify the calculation process, we divide the sample into four types: adult male, adult female, child, and elderly. The proportions of different groups are 45%, 45%, 5%, and 5%; and their body widths are 46.48, 43.91, 32.56, and 44.78 cm, respectively.

In case of a fire, a large number of evacuees will lead to congestion and panic and thereby the walking speed will slow down. This study sets the walking speeds of adult males, adult females, children, and elderly at 1.5, 1.3, 1.2, and 0.8 m/s, respectively.

4.2.3 Choice of evacuation mode

In the Pathfinder software, the evacuation modes, including the steering mode and SFPE mode, should be selected before the evacuation simulation. In case of a fire, the Required Safe Egress Time (RSET) and Available Safe Egress Time (ASET) should be established. Only when the RSET is less than the ASET can all evacuees be successfully evacuated and guaranteed safe. The RSET is calculated as follows:

Table 2 Number of evacuees.

Floor	Number of evacuees		Total number of evacuees
	Hall	Room	
First floor	760×1.1 = 836	655	1491
Second floor	680×1.1 = 748	724	1472
Third floor	880×1.1 = 968	647	1615

$$T_{\mathrm{RSET}} = T_1 + T_2 + \alpha \times T_3 \quad (1)$$

$$T_2 = 120 + \sqrt{A_0} + 0.4H \quad (2)$$

where T_1 is the fire detection alarm time, which is set to 60 s; T_2 is the personnel reaction time; T_3 is the evacuation movement time; α is the safety factor, which is set to 1.1; A_0 is the floor area, which is 11 119 m^2; and H is the floor height, which is 15.3 m.

$$T_2 = 120 + \sqrt{11\,119} + 0.4 \times 15.3 = 231.57\ \mathrm{s}.$$

Take the holistic evacuation only by stairs as an example. The evacuation movement time of the evacuees in steering and SFPE modes is 458.3 and 533.3 s, respectively.

In steering mode,

$$T_{\mathrm{RSET}} = 60 + 231.57 + 458.3 \times 1.1 = 795.7\ \mathrm{s}.$$

In SFPE mode,

$$T_{\mathrm{RSET}} = 60 + 231.57 + 533.3 \times 1.1 = 878.2\ \mathrm{s}.$$

As the steering mode is characterized by a short evacuation time and high evacuation efficiency, it is selected to simulate evacuees' evacuation.

5 Evacuation Strategies of Simulation Model

To find the most efficient evacuation strategy, we construct an evacuation model involving a stair–fire elevator combination and design four evacuation strategies, namely, stratified evacuation only by stairs, stratified evacuation mainly by stairs and supplemented by fire elevators, holistic evacuation only by stairs, and holistic evacuation mainly by stairs and supplemented by fire elevators. When the evacuation time is less than the tolerance limit time, the evacuation strategy is deemed reasonable; otherwise, it is unreasonable. Through the data analysis of congestion problems, congestion locations, and design defects in the evacuation process, we can determine the most effective evacuation method and optimize the building's structural design.

According to the CAD drawings, a fire elevator is situated on the left side of the restaurant door, and it can be used by firefighters in case of a fire. At present, only fire elevators can be used in case of a fire, according to the Chinese government. We thus select the fire elevator as an evacuation aid.

5.1 Stratified evacuation only by stairs

In the stratified evacuation only by stairs, all evacuees use the stairs to evacuate, and the fire elevator is not utilized. The most commonly used method is to evacuate the evacuees on the first floor, then the second floor, and finally the third floor. This method can avoid the friction between the personnel and effectively control the evacuees' density. Through simulation, the single evacuation time on the first floor is 82 s, the second floor alone evacuation time is 245.3 s, and the third floor alone evacuation time is 360 s. The evacuation time for all people outside is 687.3 s, which exceeds the evacuees' tolerance limit time of 523 s. The evacuation strategy was unreasonable.

5.2 Stratified evacuation mainly by stairs and supplemented by fire elevators

In this strategy, evacuees are mainly evacuated through stairs, and fire elevators play an auxiliary role. This evacuation method helps to avoid friction between floors and speed up the evacuation. This strategy needs to determine the proportion of people evacuated through stairs and fire elevators. After several rounds of trials, the results show that when 90% of people (mainly young) are evacuated through stairs, and 10% (elderly and children) are evacuated through fire elevators, evacuation time can be reduced to a minimum. In the simulation process, we add two options for evacuees, that is, they can go to any exit and any fire elevator, and we set the proportion of the above two kinds of people as 90% and 10%, respectively. The results show that the evacuation time on the first floor is 82 s, the evacuation time on the second floor is 243.8 s, and the evacuation time on the third floor is 346.8 s. The evacuation time for all people outside is 672.6 s, which exceeds the personnel tolerance limit time of 523 s. This evacuation strategy is also unreasonable.

5.3 Holistic evacuation only by stairs

Holistic evacuation only by stairs means that all evacuees use the stairs and evacuees of each floor are evacuated at the same time. The disadvantage of this evacuation method is that it might cause congestion or friction, but it can save evacuation time. After simulation, the overall evacuation time is 458.3 s, which is lower than the evacuees' tolerance limit time of 523 s, and this evacuation strategy is feasible.

5.4 Holistic evacuation mainly by stairs and supplemented by fire elevators

In holistic evacuation mainly by stairs and supplemented by fire elevators, most young people take the stairs to evacuate, and the rest are instructed to evacuate using the fire elevators. According to the simulation, the overall evacuation time for this strategy is 374 s, which is 84.3 s less than that in the holistic evacuation only by stairs and is less than the evacuees' tolerance limit time. This evacuation strategy is feasible.

6 Analysis and Discussion of Evacuation Results

6.1 Evacuation time and evacuees' pass rate in each export

Given the parameters we set in the case study, we further provide the relationship between the evacuees in the canteen and the evacuation time (Fig. 6). The results suggest that the number of evacuees continues to increase over time and that the evacuation speed increases first and then decreases.

6.2 Analysis of stratified evacuation method

(1) The evacuation time increases as the number of floors increases mainly because the stairs are narrow and the revolving design is prone to congestion.

(2) The advantages of the strategy supplemented by fire elevators are insignificant for the lower floors. Hence, such a strategy might be most suitable for high buildings. Figure 7 shows the pass rate of the evacuees on the second floor. The utilization rate of exit 2 is 0 when the second floor is evacuated separately. The architectural design drawing of this canteen shows that exit 2 is relatively far from the stairs and is located at the corner of the first floor and traverses a narrow path. The utilization rate of exit 2 is 0 because no evacuee takes it. Therefore, this exit suffers from some design defects.

(3) The pass rate of exit 3 is low when the third floor is evacuated separately. Staircase 1, which is nearest to exit 3, only leads to the second floor and is far from the other stairs on the second floor. Evacuees moving from the third floor to the second floor often do not choose this exit to go to the first floor. Thus, the utilization rate of exit 3 is also very low, and this exit suffers from design defects.

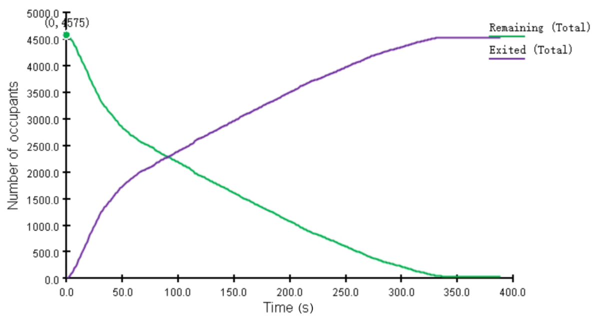

Fig. 6 Relationship between evacuees in the canteen and evacuation time.

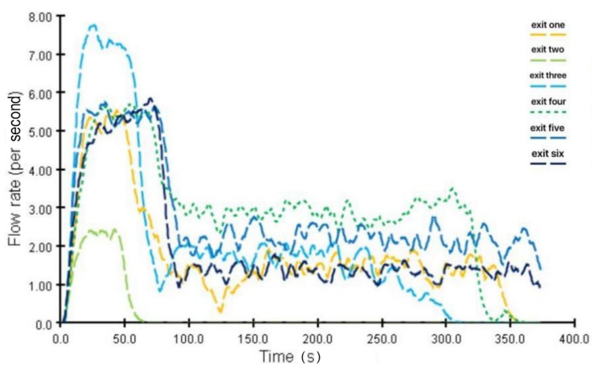

Fig. 7 Evacuees' pass rate in each exit.

6.3 Analysis of holistic evacuation method

(1) Figure 7 shows that exit 4 has the highest pass rate. On one hand, exit 4 is close to the outdoor stairs (staircase 2) and can thus prevent contact and friction between indoor evacuees. The evacuation efficiency at exit 4 is also high. On the other hand, the stairs are one way, thereby reducing personnel congestion.

(2) When the people on the second and third floors do not reach the first floor (100 s before), the evacuation efficiency of the evacuees on the first floor is high. However, as the number of evacuees increases, congestion becomes severe, and the evacuation efficiency drops sharply.

Holistic evacuation, mainly by stairs and supplemented by fire elevators, is used as the evacuation mode for large public buildings in case of a fire. According to the data, this strategy results in the shortest evacuation time and meets the basic conditions for safe evacuation.

7 Model Improvement and Results

7.1 Model improvement

When a fire occurs in a large public building, casualties and property losses are likely during the evacuation process if the design of the building structure is unreasonable. By comparing four different evacuation strategies and the individual evacuation conditions for each floor, we find certain defects for exit 2 and staircase 2 directed toward the second floor in the middle of the hall in the structural design of the canteen. When the second floor is evacuated individually, exit 2 is set far away from the stairs. It is located at the corner of the first floor and traverses a narrow aisle. People evacuating from the second floor to the first floor would not choose exit 2. When the people on the third floor are evacuated individually, the utilization rate of staircase 2 is almost 0 as it is not connected to the third floor. At the same time, the utilization rate of exit 3 decreases.

According to the above two defects in the architectural design, we provide two improvements: One is to modify the position of exit 2 such that it is close to the flow of evacuees and need not have evacuees traverse any passages; the other is to extend the stairs facing exit 3 to the third floor so that people on the third floor can choose staircase 2 from the third floor to the first floor. The latter improvement can increase the utilization rate of the stairs and facilitate the evacuation of the third floor.

7.2 Improved results

Through simulation, the improved holistic evacuation mode can save 24 s and improve evacuation efficiency by about 6% relative to the previous one. The pass rate of each exit after the improvement is shown in Fig. 8.

The evacuees' pass rate in each exit greatly increases after the change of the position of exit 2. Exit 3 is used until the evacuation is completed, and the evacuees' pass rate is subsequently improved.

8 Conclusion

In this work, we construct an evacuation model that combines stairs and fire elevators in a large public building by using BIM technology and evacuation simulation technology. We consider the limited time of crowd tolerance under the influence of various fire factors. Through the simulation of four evacuation strategies, we conclude that holistic evacuation mainly by stairs and supplemented by fire elevators is the most efficient. By combining the simulation results and the architectural design drawings, we improve two design defects and thereby increase the evacuation efficiency and exit pass rate of the improved model. Our research provides some references for the evacuation modes of large public buildings in case of a fire. It is also expected to benefit the optimal design for building fire prevention.

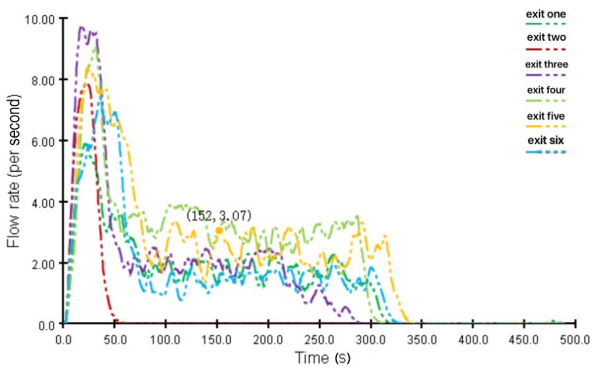

Fig. 8 Improved evacuees' pass rate in each exit.

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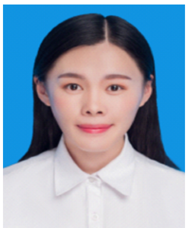

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