Simulation of Emergency Evacuation from Construction Site of Prefabricated Buildings

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Abstract

To ensure the safe construction of prefabricated buildings and improve the efficiency of the safe evacuation of construction personnel after a fire caused by improper operation during construction, this study used the PyroSim software to numerically simulate a fire situation based on the size and volume of a prefabricated building construction site. The variation rules of smoke visibility, CO concentration, and ambient temperature in the construction site of prefabricated buildings were analyzed and the available safe evacuation time was determined. Moreover, the Pathfinder software was used for simulation in combination with the physical attributes of personnel, evacuation speed, and personnel proportions. The time required for safe evacuation was determined and the factors influencing the evacuation time, such as the quantity and location of stacked prefabricated components, machinery, and appliances, and the number of on-site construction personnel, were analyzed. The results reveal that the original layout of the prefabricated building construction site cannot facilitate the safe evacuation of all construction personnel. The bottleneck area for the evacuation of construction personnel is the indoor corridor and evacuation stairway. The quantity and location of stacked items at the construction site greatly influence the evacuation time. When the number of construction personnel on each floor reaches a certain value, restrictions should be imposed. The results obtained by this study can provide the theoretical basis for the rational planning of evacuation routes and construction site management.

1. Introduction

With the rapid development of China's economy, the level of urbanization is further accelerating and prefabricated construction is rapidly developing owing to its advantages of low carbon emissions, environmental efficiency, high technological content, and management innovation. When COVID-19 broke out in China in 2020, Huoshenshan Hospital and Leishenshan Hospital were built in only 10 days. The high efficiency, low cost, and reduced pollution advantages of prefabricated buildings have resulted in the construction market fully realizing the efficiency and advantages of prefabricated building construction in emergency situations. However, owing to the frequency of accidents in the construction industry, the safety of human lives and property are of great concern, and more attention is being directed toward the safe evacuation of construction personnel from assembly construction sites, which is gradually becoming a hot research topic domestically and abroad. Wu [1] used the Pathfinder software to simulate the evacuation process in an office building construction site, and optimized the construction schedule and site layout using the evacuation simulation results in combination with various rules. Wang et al. [2] used the PyroSim software to numerically simulate a fire situation, and analyzed the change rules of smoke visibility and environmental temperature at each stair exit of the office building when the fire occurs under the failure of the automatic fire extinguishing system, fire door failure, and so on. Moreover, they conducted evacuation simulation using the Pathfinder software. The influence of the total number of evacuees, environmental temperature, and environmental visibility on the evacuation efficiency was analyzed. Wahyu Sujatmiko et al. [3] used the FDS and EVAC software to simulate the emergency evacuation of a high-rise residential construction project, analyzed the spreading law of smoke based on

the principle of fluid dynamics, and assessed the safety of the emergency evacuation of construction personnel from high-rise buildings. Ruggiero et al. [4] experimentally analyzed the influence of people's behavioral habits on the evacuation process, and compared the differences between the experimental data and the simulation results obtained for the evacuation behavioral rules using the FDS and EVAC software. Helbing[5] used the social force model to simulate the evacuation process in the case of fire, and set up traffic signs at particular positions inside the building to guide the evacuation under emergency conditions. Nishinari et al. [6] used a CA model to simulate a safe personnel evacuation, analyzed the positions of obstacles in the building, and optimized the site layout in accordance with the analysis results. Yu [7] used the Pathfinder software and considered different structural units to conduct a simulation and assess the impact of the room entrance location, length of the evacuation time, and impact of the evacuation efficiency. The influences of width, Angle, quantity and total width on evacuation were studied by building structural models of corridor exits with different crowd densities. Liu [8] used the Pathfinder software to simulate the safe emergency evacuation of primary school personnel and comprehensively analyzed a school building. They analyzed the influence of traffic space design, personnel behavior, psychological fluctuations, and other factors on the evacuation time under fire conditions, and proposed optimization measures for the shortcomings of existing programs. Xie et al. [9] used PyroSim and FDS to model and numerically simulate a fire situation, and analyzed the temperature, toxic and harmful gases, and visibility to determine T_{ASET} . Moreover, an evacuation simulation was conducted using Pathfinder to determine the required evacuation time and analyze the congestion problems during the evacuation process. Sun et al. [10] jointly used the PyroSim and Pathfinder software to numerically simulate the spread of fire and developed rules for different emergency evacuation situations. A model was established to simulate the fire and evacuation of typical school buildings. According to the results and data obtained from the simulation, the change laws of the spread of fire, smoke diffusion, toxic gas concentration, temperature distribution, and visibility, were analyzed. Many other studies have conducted simulations to investigate the organized evacuation of on-site construction personnel [11–15].

However, existing studies have not considered the influence of smoke diffusion and reduced visibility on the evacuation process. The influence of personnel distribution on the evacuation has also not been considered. Therefore, research on evacuation simulation and emergency rescue route determination under extreme circumstances is currently lacking. This study considered the construction site of a prefabricated building as an example. Owing to the particularity of prefabricated construction, a large number of assembly components must be piled up in the construction site. Therefore, this study focused on the influence exerted by the number and location of items and number of operators on the evacuation time. The PyroSim and Pathfinder software were used to conduct a numerical simulation. The effects of ambient temperature, CO concentration, visibility, personnel composition, and number and location of obstacles on the evacuation were analyzed. The findings of this study provide the basis for fire safety management, the evacuation of personnel during a fire emergency, and the preparation of an emergency plan for assembly building construction sites.

1. Smoke diffusion law and general framework for evacuation of personnel from prefabricated building construction site

To adapt to the development trend of prefabricated building construction in China and reduce the casualties caused by poor evacuation strategies during the construction of prefabricated buildings, this study considered a prefabricated talent apartment project as an example to investigate macro evacuation strategies that can be used in the case of fire. Building information modeling (BIM) technology was used to construct a parametric information model, and the fire dynamics software Pyrosim and Pathfinder were used to conduct an FDS smoke simulation and analyze the emergency evacuation of personnel from a prefabricated building construction site in the case of fire. First, the Revit software was used to establish the building information model into the PyroSim and Pathfinder simulation software for fire smoke analysis and evacuation analysis, respectively. The flue gas layer height, flue gas temperature, visibility and CO concentration in different areas are analyzed by Pyrosim software. The available evacuation time (T_{ASET}) for personnel in different operating areas was obtained. Additionally, the T_{RSET} (evacuation time) of construction personnel in the case of fire at an assembly building construction site was obtained through a Pathfinder simulation, and the safety of on-site personnel was assessed. Finally, Pathfinder was used to further optimize the evacuation process, such that the simulation results would more accurately reflect an actual situation. By integrating the data simulation results, a general framework for fire emergency evacuation from a prefabricated building construction site is proposed as shown in Fig. 1.

2. Numerical Modeling And Fire Simulation

2.1 Introduction to PyroSim and simulated objects

To simulate the fire development process, it is necessary to select a suitable simulation model. Through the analysis of such models, an intuitive understanding of the fire spreading process can be gained, and the temperature field distribution, smoke distribution, and visibility distribution in the fire scene can be qualitatively and quantitatively analyzed [16]. Presently, the main fire simulation software are as follows: DETACT-QS, used to calculate the power of the fire source; FDS, FLUENT, and CFAST, used to calculate fire smoke distribution, and so on. The application of FLUENT and other software to fire simulations requires a strong fluid mechanics background, which renders them unsuitable for use in this study. The FDS software is specifically developed for fire simulations and is the most widely used fire simulation software owing to its ease of use.

The FDS software was developed by the Building Fire Laboratory of The National Institute of Technology and Standards to calculate the fire dynamics. The FDS software can be used to simulate and analyze the smoke spreading process [17], carry out the geometric modeling of building structures, set the monitoring position of fire information such as the wall thermal conductivity parameters, fire type, smoke temperature, and visibility, and investigate the change law of the fire parameters during the combustion process. At the same time, the simulation results can be visually viewed by Smoke View software,

including temperature, Smoke concentration, Smoke speed and other parameters of the plane distribution, Smoke spreading process. As a pre-processing software for FDS, PyroSim can be used to quickly build models, set the parameters, and adjust the monitoring point settings, in addition to other functions. PyroSim has the following characteristics and capabilities:

- (1) Hydrodynamic modeling. The Neville–Stokes equation can be used to quantitatively calculate thermally driven, low-velocity fluids.
- (2) Combustion modeling. Different combustion reactions can be set up and simulated by setting the combustion mixture.
- (3) Radiative transport. Radiative transport equations can be used to calculate the radiative transport.
- (4) Unique geometry. The software allows the setting of obstacles.
- (5) Boundary conditions. The thermal boundary conditions of the materials can be defined, and the combustion characteristics can be set.

Therefore, this study selected PyroSim to numerically simulate the fire scene of an assembly building construction site.

The prefabricated building talent apartment project considered in this study is designed to facilitate education and scientific research. The land area is 13,719.29 m², the total construction area is 45,641.49 m², the considered construction area is 3313.74 m², the plot ratio is 4.31, and the building density is 24.15%. The project effect is shown in Fig. 2. The structural form of the project is a frame shear wall structure, and the assembled components are a composite floor slab, composite beam, external wall hanging plate, light partition wall, precast staircase, and so on, with a precast rate of 30.53%. After the installation of the precast components, the entire post-cast concrete is combined with the frame column beam and so on.

This study considered building #F02 of the Talent apartment complex as an example for establishing a safety information model. The talent apartment building consists of two high-rise buildings, the fire protection rating is One, and each floor has two evacuation stairs. The building has 13 floors and a total height of 40.95 m. The ground floor is equipped with a duty room, public laundry room, storage room, and so on. The 2nd to 13th floors consist of two-room student dormitories that can accommodate 720 students. The room space in a standard floor of the prefabricated apartment project is narrow and restricted. Hence, a fire explosion can easily be caused when fire occurs. There is no spraying and mechanical smoke exhaust system in the building, and doors and windows are not installed; therefore, natural smoke exhaust conditions were considered in this study.

2.2 Model Building

A prefabricated apartment building with a height of 3.3 m and a total of 13 floors was considered as the object to be modeled. In this study, the Revit software was used to establish the physical model of fire in a prefabricated building, and the Revit model was then imported into PyroSim. The model renderings and standard floor plans are shown in Figs. 3 and 4. Using the ratio of 1:1, the simulation model was constructed and the model area was divided into grids to simulate a fire scene. If the grid division is too large, it may not accurately calculate and describe the change of the environmental parameters in the fire scene. If the grid division is too small, the accuracy of the simulation calculation will be higher, which may result in excessively long or infeasible calculation. Therefore, by comprehensively considering the calculation accuracy, this study adopted the uniform mesh partition method, and the mesh size was set to 1 m × 1 m × 1 m.

2.3 Fire Hazard Determination

2.3.1 Analysis of factors influencing fire at prefabricated building construction site

According to relevant statistics, most human casualties during a fire are caused by the inhalation of smoke and toxic gas coma before death. When a fire breaks out, the factors that can threaten the safe evacuation of people are the smoke visibility, toxic smoke (mainly CO), and heat radiation from the fire source [18]. The CO concentration, flue gas temperature, flue gas layer height, and flue gas visibility are the main performance parameters. Therefore, the critical values of human tolerance to these parameters should be analyzed to determine whether a fire situation has reached the dangerous state.

(1) Smoke layer height

The height of the smoke layer determines whether the smoke will affect the human body. The high-temperature smoke produced in a fire will rise to the upper space of the building under the action of thermal buoyancy. When the smoke encounters the roof of the building, it accumulates and gradually thickens to form a smoke layer. As the smoke continues to rise and the smoke layer continues to thicken, the height of the smoke layer gradually decreases; when the height drops to the height of the fire, harm is caused to the personnel and the evacuation process is greatly affected. Therefore, the smoke layer should be kept above a certain height to ensure the safety of personnel and rapid evacuation to a greater extent. One of the quantitative assessment criteria is that the height of the smoke layer should satisfy the following formula in the process of personnel evacuation.

$$H_S \geq H_C = H_P + 0.1H_B \quad (1)$$

where H_S is the clear height (m); H_C is the critical height (m); H_P is the average height (m) and typically amounts to 1.6 m; H_B is the height inside the building (m).

The average height of the investigated prefabricated apartment project was approximately 3.3 m. According to Equation 1, the critical height $HC = 1.6 + 0.1 \times 3.3 = 1.93$ (m). Therefore, the height of 2.00 m above the ground was considered as the critical height of the smoke layer.

(2) Flue gas temperature

When a fire breaks out, hot smoke is typically produced, and people breathing the overheated air may suffer heat stroke and skin burns. Because thermal radiation data cannot be obtained directly, it is necessary to determine the critical temperature that the human body can withstand by analyzing the fire hazard conditions. The tolerance times of the human body under different conditions are listed in Table 1. The critical value of the selected temperature is 60°C.

Table 1
Limit of human body tolerance to hot air [19].

Temperature and Humidity	<60°C, Water saturation	60°C, Moisture content <1%	100°C, Moisture content <1%
Tolerance time (min)	>30	12	1

(3) CO concentration

A large amount of high-temperature smoke is produced during a fire, and the many types of combustibles in buildings, including various toxic and harmful gases and solid particles, among which the CO content is the largest and most harmful to the human body, result in complex fire smoke composition. After CO gas poisoning, carbonyl hemoglobin is produced in the blood and affects the human respiration and nerve reaction. The degrees of harm of different CO concentrations to the human body are listed in Table 2. According to the hazard assessment, the CO concentration of 500 ppm is determined as the critical value for the emergence of danger.

Table 2
Degree of harm to human body of different CO concentrations [19].

CO concentration of flue gas (ppm)	Time (min)	Degree of hazard
200	120–180	Mild headache and fatigue
400	60–120	Secondary headaches
800	45	Unconsciousness, vomiting
1600	20	Headache, dizziness, nausea
3200	10–15	Death

(4) Smoke visibility

The visibility of flue gas determines people's capability of assessing the surrounding environment and recognizing the evacuation passage and safety exit, the perception and decision-making process of

trapped personnel, the escape time, and other factors affecting the efficiency of an emergency evacuation. Low visibility results from the blocking of light by the solid particles in flue gas. In a low-visibility environment, the suspended solid particles stimulate the eyes, make it difficult for trapped people to accurately assess the surrounding environment, and reduce people's ability to recognize the evacuation channels and safety exits, which results in perceptual decision-making mistakes and missing the optimal escape time. The Australian "Fire Engineer Guide" specifies the critical value of visibility for spaces with different size. The critical value of visibility is 10 m in a large space and 5 m in a small space [20]. The investigated prefabricated apartment project has small space; therefore, the smoke visibility index is 5 m.

2.3.2 Fire Hazard Determination Conditions

Through the analysis of the above-mentioned factors influencing the safety of personnel evacuation, the temperature, CO concentration, and visibility conditions in the fire scene should be set to ensure the safe evacuation of construction personnel. This study set the fire risk assessment conditions of the prefabricated apartment project as follows:

- (1) Temperature assessment conditions: a smoke layer temperature exceeding 60°C at a height of 2.00 m above the ground is considered as a fire danger state.
- (2) CO concentration assessment conditions: a CO concentration greater than 500 ppm at a height of 2.00 m above the ground is considered as a fire danger state;
- (3) Visibility assessment conditions: if the visibility of the smoke layer at 2.00 m above the ground is less than 5 m, it is considered that the fire has reached the dangerous state.

2.4 Fire Scene Setup

Initial simulation environment: the flow field in the room is static, the temperature is 20°C, and the pressure is standard atmospheric pressure. A building fire has the characteristics of fast spread, difficult management, and high rescue difficulty. Because the prefabricated building is under construction, there is no automatic fire extinguishing system, smoke exhaust system, or other similar equipment, and the construction situation of each part must be analyzed simultaneously. Two ignition sources were set in the numerical simulation study. The first fire was located in the left corridor on the 2nd floor of the lower level, and the second fire was located in the left corridor on the 11th floor of the higher level. To monitor the spread of office building fire and the visibility and temperature change characteristics of the escape routes, several temperature sensors, CO concentration detectors, smoke layer height detectors, and visibility detectors were set in the fire layer and upper and lower adjacent layers. The height is 2m above the ground of this layer, as shown in Figure 5.

2.5 Analysis Of Fire Simulation Results

2.5.1 Fire smoke spread analysis

Figure 6 shows the process of simulating the spread and filling of smoke in an office building after a fire. As can be seen from the simulation results presented in Fig. 6 (a)–(f), As can be seen from the simulation results in FIG. 6 (a) ~ (f), smoke mainly collects around the fire source in the initial stage of fire combustion when the fire occurs 30 seconds. Sixty seconds after the fire has broken out, the hall on the left side of the 2nd floor and 11th floor is filled with smoke spreading rapidly upward through the stairwell and elevator shaft. At 110 s after the onset of fire, the smoke from the fire source on the 11th floor spreads to the top floor, and the smoke from the fire source on the second floor spreads to the talent apartment through the west window. At this time, the smoke does not fill the entire corridor on the second floor. As the fire develops, the smoke continues to spread, and the smoke concentration gradually increases. At $t = 160$ s, the east, middle, and west areas of the 2nd and 11th floors are completely filled with smoke. At 200 s after the fire occurs, the floors adjacent to the fire floor are completely filled with smoke. Three hundred seconds after the fire has broken out, the smoke continues to spread and all floors except the first floor are filled with smoke. Approximately 75% of the entire office building is filled with smoke.

2.5.2 Temperature Change Analysis

The temperature change curve and the temperature change slice diagram is drawn in Figs. 7 and 8. According to the temperature change data obtained by the temperature sensor. By analyzing the temperature change curve, the following conclusions are obtained: (1) the fire location exhibits approximately the same change trend, which reveals that, after the initial stage of fire combustion, the temperatures soars to the maximum temperature fluctuation and then declines. With the spread of the fire, the temperature began to rise after reaching the lowest point, and the temperature tended to be stable with the development of time. (2) When fire occurs, the temperature at the fire source linearly increases, which can easily cause severe threats to the life and safety of personnel close to the fire source. Hence, it is very important for people to escape the danger immediately and stay away from the fire source. (3) The temperature change trend at the exit of the stairs is the same and the temperature change is relatively slow; as the distance to the fire decreases, the temperature change becomes faster. According to the above discussion, the ambient temperature limit of the human body is approximately 60°C, and the data of six sensors exceed 60°C within 350 s.

2.5.3 Co Concentration Change Analysis

Under the action of plume, the buoyancy of the flue gas increases and the flue gas rapidly rises to the ceiling. The produced flue gas jets to the ceiling and rapidly spreads to both sides of the corridor along

the ceiling. The carbon monoxide concentration is maximum at the detection point farthest from the fire source, where a large amount of flue gas has accumulated. Under the positive chimney effect, hot flue gas is gradually injected into each floor over time. The flue gas in the stairwell is affected by the positive chimney effect, and the temperature of the flue gas increases; therefore, the flue gas produces greater buoyancy. Under these conditions, a large number of high temperature flue gas moves to the upper layer. However, during the movement, the flue gas is hampered by the staircase structure, and a large amount of high temperature flue gas accumulates at the stairs, which leads to a further increase in the flue gas temperature. Hence, the flue gas produces stronger buoyancy, and the temperature flue gas action is high until the gas moves to the top of the stairs. Additionally, at 11 layer detection points, the carbon monoxide concentration is higher relative to other floors, and thus more dangerous, as shown in Figs. 9 and 10. When the height of the smoke layer is smaller than the height of the human eye, the carbon monoxide concentration at all detection points does not reach the critical value during the simulation time, and the carbon monoxide is not harmful to humans.

2.5.4 Visibility Change Analysis

In the process of combustion, solid and liquid particles are produced in large numbers, which greatly affects the visibility of the fire site and produces great resistance for the emergency evacuation of personnel and the smooth extinguishing of the fire. Therefore, this study installed visibility sensors at the same positions as the temperature sensors. The visibility curve was drawn according to the sensor data. As shown in Figs. 11 and 12, in the early stage of the fire, the visibility of the floor was approximately 30 m and decreased exponentially as smoke filled the office building with the spread of fire. Owing to the impact of the fire source on the 11th floor, the visibility of the sensor decreased very early. The visibility dropped to 5 m in 50 s and reached the danger point for casualties. At approximately 400 s, the data collected by all visibility sensors reveal that the visibility at each exit was less than 5 m. The optimal escape time elapses after 400 s.

3. Establishment Of Numerical Model And Emergency Evacuation Simulation

3.1 Evacuation software contrast with Pathfinder software Introduction

At present, several types of evacuation simulation software are widely used (Pathfinder, FDS + EVAC, Building Exodus, Steps, Simulex, and so on) and their application scopes are listed in Table 3. Pathfinder is an intelligent evacuation evaluation software²¹ that is simple to use, visually intuitive, and convenient to apply. Additionally, Pathfinder is suitable for large complex buildings and has the following advantages:

- (1) The software contains its own internal modeling system, and additional formats can be used through the import of modeling files.
- (2) The model has fast calculation speed and can handle the evaluation and analysis of large complex buildings for personnel evacuation research.
- (3) The software comprehensively considers the parameters affecting personnel evacuation and can more accurately calculate the personnel evacuation situation at a specific building in a specific scene.
- (4) The software can partition the building model and simultaneously determine the evacuation process and escape route for people in designated positions on different floors.

Therefore, this study selected the Pathfinder software to numerically simulate the process of evacuating Prefabricated building construction site staff.

Table 3
Common evacuation simulation software and its applicable scope

Software Brand	Scope of application
Building EXODUS	Airports, stations and other large Spaces and buildings with large escape crowd
FDS+Evac	Labor-intensive factories, stadiums and other public places and large vehicles
Pathfinder	Suitable for large buildings
Simulex	Suitable for large, complex geometrical buildings with multiple floors and staircases
STEPS	Various building types and vehicles

Pathfinder is an emulator based on personnel evacuation and movement simulation.²² The software is a three-dimensional (3D) mesh model that simulates evacuation under normal and emergency situations. The Pathfinder software can define the parameters of pedestrians. After the evacuation begins, the pedestrians will respond to changes in the evacuation environment and select the optimal evacuation path.²³

3.2 Establishment Of Emergency Evacuation Environment

To satisfy the requirements of the evacuation simulation, this study converted the safety information model of an assembly-type talent apartment project into the DXF format and imported it into Pathfinder software. The model was simplified, and the floor, stairs, doors, other components, and evacuation routes were identified. The BIM safety information model, Pathfinder evacuation model, and personnel distribution in an evacuation scenario are shown in Figs. 13 and 14.

3.3 Setting Of Emergency Evacuation Barriers

Prefabricated construction is complex and ever-changing, and the construction process, construction environment, and change of construction plane greatly influence the speed of personnel evacuation, evacuation zone, and evacuation path. In this paper, obstacles such as prefabricated components and construction instruments are set up according to the on-site construction status of prefabricated buildings, as shown in Fig. 15.

3.4 Set Emergency Evacuation Parameters

To establish a safe evacuation simulation, the behavior of people trapped at a specific location and in a certain environment must be simulated. The evacuation personnel, evacuation location, and evacuation environmental conditions are the main considerations in the simulation of safe evacuation [24]. Owing to the particularity of the prefabricated construction industry, the on-site construction personnel consist of basic assembly technology workers and manual laborers, and these laborers can be divided into four categories: young men, middle-aged men, and young and middle-aged women. Different types of personnel escape velocity have a larger difference, and the evacuation simulation software will conduct evacuation simulation according to the set personnel attribute characteristics. Additionally, the working face of the main body of the assembly building in the construction stage can be divided into two types: floor plane and stair plane. The speed of different types of personnel on different working faces must be set before the evacuation simulation.

(1) Set staff signs

The parameters and proportions of the physical personnel attributes are listed in Table 4.

Table 4
Physical sign parameters and proportions of construction personnel.

Personnel category	Young men	Young women	Middle-aged men	Middle-aged women
Shoulder breadth (cm)	41.0	38.0	41.9	39.5
Thick chest (cm)	25.8	25.7	26.4	26.6
Proportion (%)	40.7	18.5	29.5	11.3

(2) Set staff speed

According to the investigation and analysis of the evacuation speed of construction personnel on the assembly building site [1], the personnel speed was set as presented in Table 5.

Table 5
Evacuation speed of different types of personnel on different working surfaces.

Category Working plane	Young men (m/s)	Young women (m/s)	Middle-aged men (m/s)	Middle-aged women (m/s)
Plane	1.95	1.79	1.84	1.68
Stair surface	1.25	0.98	1.19	1.03

(3) Behavioral pattern settings

The behavioral modes of Pathfinder software are the SFPE mode and steering mode. In the case of an emergency, site construction personnel exhibit three behavioral modes: the shortest distance behavioral mode, the consistent in -and -out behavioral mode, and the complete conformity mode. According to the data analysis, approximately 20% of people will wait in line at the same place, while approximately 50% of people will choose another evacuation route. The steering mode can control the evacuation of personnel by combining path planning, the guidance mechanism, and collision processing. Therefore, this study selected the steering mode of emergency evacuation.

3.5 Analysis Of Evacuation Simulation Results

The simulation of the safe evacuation of construction personnel was carried out based on the determination of the above parameters. As shown in Fig. 15, a large number of prefabricated components, construction tools, and other items were piled up on the construction site of the prefabricated building, and many items were stacked around the evacuation corridor and stairs. When an emergency occurs, these items are likely to block people's evacuation path, and the evacuation speed will be greatly reduced. Therefore, the number and location of stacked items on the assembly building construction site and the number of people on each floor were the focus of the emergency evacuation. Because there are different construction stages and the flow of the construction site personnel is relatively complex, the number of evacuees at the construction site could not be accurately determined in this study. Based on the principles of the most unfavorable apartment and taking the construction plane model of the 11th floor of the higher fire floor of building F02# of talent apartment project as reference, and according to the actual personnel investment situation of the construction site of prefabricated building, the simulated site construction personnel was set to 100 people, who were assumed to be randomly distributed in different working areas on the 11th floor. Thus, the emergency evacuation simulation was carried out.

(1) Results of evacuation simulation

The results of the evacuation simulation are shown in Figs. 16 and 17. A total of 100 on-site construction personnel were evacuated in 185.8 s. Figure 18 shows the personnel density diagram at the evacuation

time of 13.0 s. As can be seen, the evacuation corridor and stairway are the areas with the highest personnel density, where evacuation corridor and stairway traffic jams can easily occur. However, there are two evacuation staircases on the east and west sides of the construction site of the talent apartment project. Therefore, prefabricated materials and mechanical appliances and other items must be removed from the evacuation corridors and staircases.

(2) Safety determination

When fire breaks out in a university library building, the safe evacuation of on-site personnel mainly depends on the time required for safe evacuation (T_{REST}) and the available time for safe evacuation (T_{ASET}). The on-site personnel can be safely evacuated only when the following formula is satisfied, otherwise the scheme should be adjusted.

$$\text{Required time for safe evacuation } (T_{REST}) \leq \text{Available time for safe evacuation } (T_{ASET}) \quad (2)$$

Here, (T_{REST}) refers to the time needed for all on-site personnel to be evacuated to safety from the moment when the emergency is discovered; (T_{ASET}) refers to the time limit after which the on-site personnel are exposed to the risk of external accidents after the occurrence of a fire.

$$\text{Required time for safe evacuation } (T_{REST}) = \text{Alarm time } (T_{alarm}) + \text{Response time } (T_{pre}) + \text{Evacuation time } (T_{move}) \quad (3)$$

In Eq. (3), T_{move} refers to the time required to evacuate all on-site construction personnel, and is jointly determined by human attributes, psychological factors, environmental characteristics, and other factors. Therefore, T_{move} is highly uncertain. Hence, the evacuation time in domestic and overseas fire control design must be multiplied by a coefficient of 1.5–2. Additionally, T_{alarm} refers to the time when some on-site construction personnel discover the accident and notify all other construction personnel. The case selected in this study is the main stage of the assembly building construction site. Because there are few obstacles around the building and the visibility is better, it is assumed that on-site construction personnel can quickly identify the abnormal situation when a fire breaks out. Therefore, T_{alarm} was set to 60 s. Finally, T_{pre} refers to the response time of the field construction personnel after receiving instructions pertaining to the danger. Because a safety risk warning system and monitoring system were installed at the construction site of the simulation project, the response time was considered to be relatively short, and was set to 120 s.

Safety determination:

Let us consider that $T_{REST} = T_{alarm} + T_{pre} + 1.5 \times T_{move} = 60 + 120 + 1.5 \times 185.5 = 398.7$ s. According to the above formula, the available time for safe evacuation is 400 s. Moreover, the average shock time of buildings domestically and abroad is 5–7 minutes [25]; the shock time (T_{ASET}) was set to 6 min in this

study. The required time for safe evacuation (T_{REST}) > Available safe evacuation time (T_{ASET}). Therefore, the safety assessment failed, and all personnel could not be evacuated to safety.

(3) Optimization of construction site layout and number of construction personnel

The results of the first emergency evacuation were analyzed. First, the items stacked at the evacuation stairs and corridors affected the speed of personnel movement. To optimize the prefabricated materials and mechanical equipment, the obstacle positions must be optimized and specific operations must be carried out to remove items from the evacuation paths. Additionally, the obstacles blocking the indoor corridors and evacuation stairs should be transferred inside the room as far as possible and situated at the corner or on the side. Secondly, the excessive number of on-site personnel affected the overall evacuation speed. Therefore, the simulated number of the second emergency evacuation was reduced to 80 people. The optimized stacking of on-site items and personnel settings are shown in Fig. 19. A second emergency evacuation simulation was conducted with the optimized settings.

As shown in Fig. 20, the total time used in this simulation was 156.8 s. The time required for safe evacuation is $T_{REST} = T_{alarm} + T_{pre} + 1.5 \times T_{move} = 60 + 60 + 1.5 \times 156.8 \text{ s} = 355.2 \text{ s}$, and $T_{REST} = 355.2 \text{ s} < T_{ASET} = 360.0 \text{ s}$, which satisfies the code requirements for the design of building fire prevention measures. Figure 21 shows the efficiency of each staircase and entrance.

4. Conclusion

The following conclusions were drawn from this study:

1. When a fire occurs, the temperature variation at the fire source is the most obvious variation, and the temperature variation trend is approximately the same. The smoke rising through the stairwells and elevator shafts to the 13th floor is the main factor contributing to the filling of the middle area of the 13th floor with smoke.
2. Based on a prefabricated apartment, the fire simulation and emergency evacuation simulation are studied. Through in-depth analysis, it was found that the evacuation efficiency is related to the personnel density, relative position of personnel, and degree of evacuation congestion. Severe detention and congestion in the stairwell were the main reasons affecting the evacuation efficiency, and should be considered as the primary safety hazards in the prevention of actual fire emergencies.
3. Visibility variation features can guide the evacuees and assist the rescue effort. In the numerical simulation conducted in this study, the optimal emergency rescue entrance was the east escape exit.
4. The total time of the first emergency evacuation was 185.8 s. By analyzing the data collected by the temperature sensor, CO concentration sensor, and visibility sensor in the scene, it was found that the visibility and shock time are the key factors that negatively affect the evacuation efficiency. At 400 s, the visibility of the exit of the university office building was less than 5 m. The building crash time was 360 s, which reaches the danger point for casualties. When the time required for safe evacuation

(T_{REST}) > available time for safe evacuation (T_{ASET}), the safety assessment fails, and the on-site personnel cannot be completely evacuated to safety.

5. The evacuation time can be effectively reduced by reasonably planning the position where assembly construction materials, equipment, and other items are stacked to reduce the loading of the construction plane, ensure that the evacuation stairs are unimpeded, and actively provide evacuation guidance. The results of the second simulation reveal that the safe evacuation time (T_{REST}) is 156.8 s. The time required for safe evacuation (T_{REST}) < available time for safe evacuation (T_{ASET}) is in line with the requirements of the building fire prevention design code.
6. This study considered a prefabricated apartment and used the PyroSim and Pathfinder software to numerically simulate a fire and emergency evacuation, so as to determine how to effectively evacuate on-site personnel to safety during a fire emergency. The obtained results reveal that simulation technology has good potential for use in high-rise building fire simulation and evacuation research. This study considered a fixed fire point to investigate the spread of fire and the evacuation of personnel, and can provide a foundation for future work considering multiple fire points and different obstacle distributions to obtain more significant results.

Declarations

Author Contributions

Xx.P.contributed equally to this work.

Notes

The authors declare no competing financial interest.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Figures

Figure 1

General framework for fire emergency evacuation from prefabricated building construction site.

Figure 2

Architectural renderings of prefabricated apartment for talented people.

Figure 3

PyroSim model diagram.

Figure 4

PyroSim Standard layer plan.

Figure 5

Sensor relative position diagram.

(a) 30 s

(b) 60 s

(c) 110 s

(d) 160 s

(e) 200 s

(f) 300 s

Figure 6

Chart of smoke spread.

Figure 7

Temperature curve

Figure 8

Slice diagram of temperature change.

Figure 9

Curve of CO concentration change.

Figure 10

Section diagram of CO concentration change.

Figure 11

Visibility change chart.

Figure 12

Slice diagram of visibility changes.

Figure 13

BIM security information model.

Figure 14

Pathfinder model of safe emergency evacuation.

Figure 15

Obstacle setup in Pathfinder emergency evacuation model.

Run Simulation - 1.pth

Sim Time (s):

185.8

Run Time (s):

24.2

Occs Rem:

0

Occs Total:

100

DTG Max (m):

0.0

DTG Avg (m):

0.0

2	26	139.4	"00111"	187.3
3	34	141.5	"00107"	194.6
4	2	138.6	"00112"	150.1
Default	1	172.7	"00114"	172.7
all profiles	100	138.6	"00112"	196.7

☒ Show results when finished

☒ Pause if occupants appear to be stuck

Debug

Results

Pause

OK

Figure 16

Total evacuation time.

Figure 17

Evacuation time-number curve.

Figure 18

Personnel density map at evacuation time of 13.0 s.

Figure 19

Optimized stacking of building materials.

Run Simulation - 2.pth

Sim Time (s):
156.8

Run Time (s):
11.3

Occs Rem:
0

Occs Total:
80

DTG Max (m):
0.0

DTG Avg (m):
0.0

1	33	140.3	"00113"	193.5
2	21	147.8	"00111"	188.7
3	25	139.9	"00107"	182.9
4	1	139.6	"00112"	139.6
all profiles	80	139.6	"00112"	193.5

☒ Show results when finished

☒ Pause if occupants appear to be stuck

Debug

Results

Pause

OK

Figure 20

Total evacuation time (second simulation).

Figure 21

Changes in flow of people at each exit.