Scientific Research Publishing

Open Journal of Safety Science and Technology, 2024, 14, 17-28
https://www.scirp.org/journal/ojsst
ISSN Online: 2162-6006
ISSN Print: 2162-5999

Preliminary Design of New Escape Chute System for Multi-Storey and High-Rise Buildings and Simulation Analysis of Personnel Escape

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How to cite this paper: Yin, H.N. (2024) Preliminary Design of New Escape Chute System for Multi-Storey and High-Rise Buildings and Simulation Analysis of Personnel Escape. *Open Journal of Safety Science and Technology*, **14**, 17-28.
https://doi.org/10.4236/ojsst.2024.142002

Received: February 13, 2024
Accepted: June 18, 2024
Published: June 21, 2024

Abstract

With the rapid development of high-rise buildings in China, fire safety and evacuation have been widely concerned by the society. Based on many years' research on the existing evacuation forms of multi-storey and high-rise buildings, the author puts forward a New Escape Chute System (hereinafter referred to as NECS) consisting of "Double Spiral Chutes and Double Vertical High-elasticity Chutes". And the author takes a high-rise office building as an example for preliminary design, and uses special software to simulate the whole process of evacuation and escape, so as to compare and analyze the differences in escape time caused by the different evacuation methods. The research shows that the evacuation time of people can be effectively shortened by using NECS, which fully verifies the effectiveness of the system.

Keywords

Escape Chute, Double Spiral Chute, High Elasticity, Personnel Escape Simulation

1. Research Background and Content

High-rise buildings have been gradually built in China in recent decades. According to statistics, there are 2395 high-rise buildings over 150 m, 823 high-rise buildings over 200 m and 95 high-rise buildings over 300 m in China, all ranking first in the world [1]. In 2020, the number of new high-rise buildings over 200 m in China was in the forefront of the world (see **Figure 1**).

High-rise building is the inevitable result of the development of the times. Based on its own characteristics of large building area, complicated internal

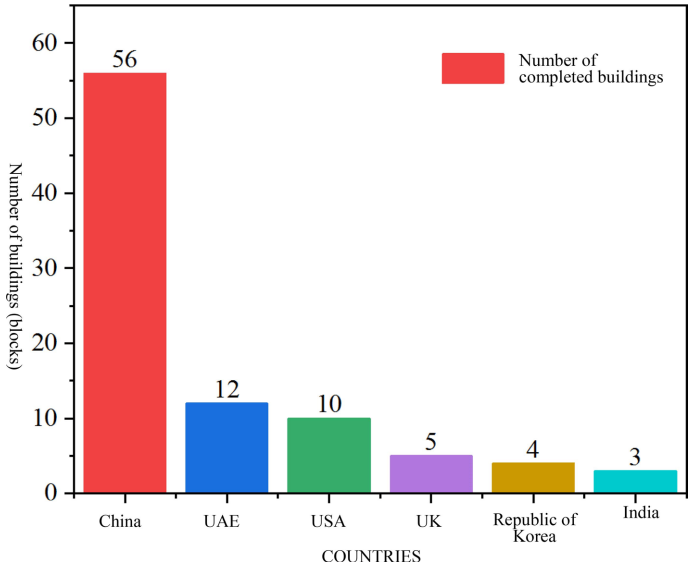


Figure 1. Number of completed buildings over 200 m in major countries in the world in 2020.

space, high population density and many fire hazards, it takes a long time for people to escape in case of fire, which is more likely to cause mass casualties and serious property losses. In addition, in view of the imperfect fire prevention technology, fire prevention specifications and fire protection system maintenance management for high-rise buildings, whenever a fire breaks out in these high-rise buildings, rescue is often not timely enough, and accidents or stampedes are easy to occur when escaping from staircase. Therefore, it is especially important to add an "alternate escape route" in high-rise buildings that can be evacuated quickly. In this paper, NECS of high-rise office buildings is proposed and designed, which is composed of "double spiral chute and double vertical high elasticity chute". Moreover, in order to verify the efficiency of NECS, a full-scale model of a multi-storey and high-rise building is established and the whole process of the personnel evacuation is simulated by using Patherfinder software.

2. Research Status of Evacuation Methods for Multi-Storey and High-Rise Buildings

2.1. Conventional Evacuation Mode

The conventional evacuation path is defined as the section from the burning room, passing through the evacuation walkway, then entering the evacuation staircase, and finally reaching the safety exit. In the Code for Fire Protection Design of Buildings (GB 50016-2014) (2018 edition), specific requirements are made for the evacuation doors, evacuation walkways, evacuation staircase and safety exits of multi-storey and high-rise public buildings [2].

2.2. Research Status of New Evacuation Forms

Researchers have designed a variety of evacuation forms for multi-storey and

high-rise buildings, among which the most typical ones are Descent Control Device, Box Type Descent Control Device, Rigid Spiral Escape Chute and Flexible Vertical Escape Chute.

2.2.1. Descent Control Device

Descent Control Device is mainly composed of governor, safety belt, safety hook, steel wire rope or fireproof lifeline, which can provide a relatively safe way to escape from high altitude [3]. Disadvantages: it requires very professional operation, requires many trainings to be proficient in using it, and it is difficult to overcome the fear when falling from the sky.

2.2.2. Box Type Descent Control Device

Box Type Descent Control Device is operated by two boxes up and down, and can be used without electricity with the air damping technology [4]. Disadvantages: complex structure, difficult daily maintenance and limited capacity of evacuation passage.

2.2.3. Rigid Spiral Escape Chute

The Spiral Escape Chute can realize the safe and efficient evacuation of people in the building. Under the action of gravity and friction, trapped people can quickly and safely slide down from high floors through the spiral escape chute.

2.2.4. Flexible Vertical Escape Chute

The Flexible Escape Chute is a vertical descending hose, which applies the principle of squeezing friction to speed limit. People enter the pipeline in sequence and begin to slowly slide down to the bottom safety area.

3. Preliminary Design of NECS

Compared with other new evacuation forms, spiral escape chute and vertical escape chute have higher evacuation efficiency, safer evacuation process and simpler evacuation mode. Inspired by the double helix structure of DNA, based on the existing research results and many years of exploration [5], the author puts forward the NECS consisting of "Double Spiral Chutes and Double Vertical High-elasticity Chutes". The author takes a 20-story office building as the preliminary target design for the Double Spiral Escape Chutes and Double Vertical Escape Chutes. The floor plan of the office building is shown in **Figure 2** and **Figure 3**.

3.1. New Double Spiral Escape Chutes

New Double Spiral Escape Chutes is mainly composed of double spiral chutes, support structure and intelligent detection equipment of chute, as shown in **Figure 4**. Many factors need to be considered in the design, such as the position and inclination angle of the chute, the material selection and arrangement of the support, and the arrangement position of the intelligent detection equipment. In the process of use, it is necessary to consider the safety of the entrance and exit

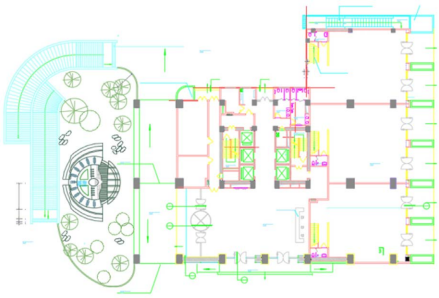


Figure 2. Floor plan of office building.

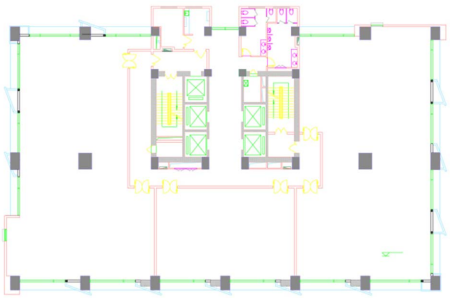


Figure 3. Floor plan of the standard floor of the office building.

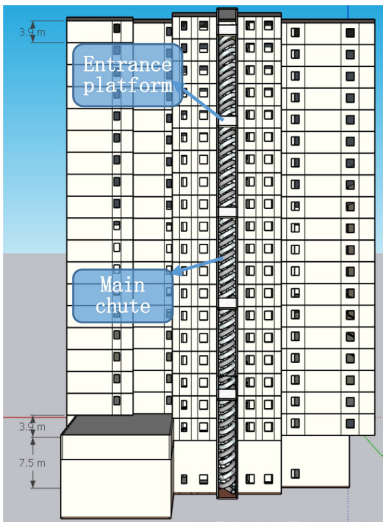


Figure 4. Front view of chute model.

of the chute and the upper and lower passages, as well as the organization of evacuation. In practical application, it is necessary to customize the escape chute system according to different building structures, topography and people flow, so as to achieve efficient, safe, convenient and reliable evacuation effect.

3.1.1. Double Spiral Escape Chutes

The Double Spiral Escape Chutes includes two spiral escape passages, which are respectively composed of a main evacuation chute, a tributary evacuation chute and a chute safety protection device. As the core of the whole chute, the main

evacuation chute runs from the top floor to the bottom floor. When designing the main chute, after selecting the appropriate chute material, it is necessary to calculate the inclination angle of the chute according to the parameters such as the building height and the turning radius of the chute:

$$\theta = \tan^{-1}\frac{h}{nR}$$

Among them:

θ : The downward inclination angle of the chute;

h : Building height;

n : The number of revolutions between each chute platform;

R: Turning radius of chute.

In the spiral chute escape system, the tributary chute aims to connect the support platform and the main chute except the top floor, so as to improve the evacuation efficiency of the chute system. The schematic diagram of the tributary chute is shown in **Figure 5**. The material, length, inclination angle and other parameters should be considered when designing the tributary evacuation chute.

The safety device of the chute includes chute sliding cushion, chute deceleration strip, exit cushion, etc. The sliding cushion is applied in the sliding process to ensure the safety of personnel and prevent personal injury caused by friction; The evacuation speed of personnel is regulated by the deceleration strip in the chute to ensure that the evacuation sliding speed of personnel is in a safe range. The exit cushion is designed to slow down the rushing speed when people leave the chute to reduce the impact force.

3.1.2. Support Structure

This part of the support structure includes a support structure and an entrance platform. The support structure of the chute is made of high-strength materials, which are arranged on both sides of the spiral chute to fix them and ensure its stability in use. The entrance platform must be made of materials with high pressure resistance and strength, and the platform size should be designed according to the radius of chute and building structure to ensure sufficient space for personnel evacuation; Secondly, considering the safety during evacuation, smoke prevention facilities are set near the entrance of the chute platform and guardrails are set at the edge of the chute, as shown in **Figure 6** and **Figure 7**.

3.1.3. Intelligent Detection Equipment for Spiral Chutes

Intelligent detection equipment includes Detection Equipment for People in the Chute, Detecting Equipment for Fire Parameters in the Chute, Chute Video Monitoring Equipment and so on. Technologies such as sensors, high-definition video monitoring and intelligent control can be used to collect, monitor and control the usage data and safety status of the whole chute, monitor and analyze the information such as the number of people, speed, behavior patterns and equipment status in real time, and adjust the usage conditions and corresponding equipment status in real time according to the data feedback and analysis results, so as to improve the safety and efficiency of the whole chute.

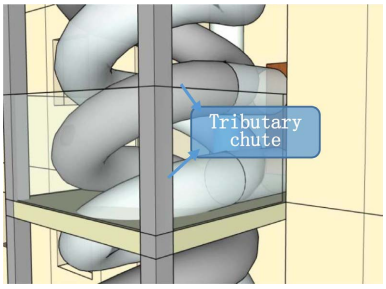


Figure 5. The schematic diagram of the tributary chute.

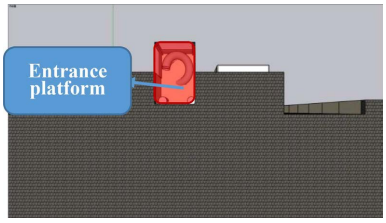


Figure 6. Top view of chute entrance platform.

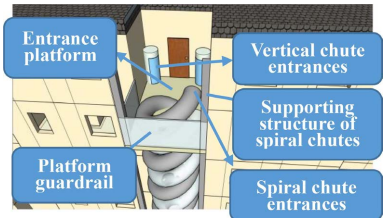


Figure 7. Chute entrance platform.

3.1.4. Organization of Personnel Flow in Spiral Chutes

The organization of personnel flow in the chute is mainly regulated by system control and personnel remote command. The number and approximate position of people in the chute are monitored by pressure sensors and temperature sensors, and the data are fed back to the chute control system, and the control system then adjusts the overall evacuation situation of the chute to ensure the safety and efficiency of personnel evacuation. In addition, in order to better cope with emergencies, a remote command system can be set up, which allows administrators to remotely control the chutes, so as to better control the evacuation and rescue work.

3.2. New Double Vertical High-Elasticity Chutes

The middle space of the main structure of the new double spiral escape chutes can be utilized and the new double vertical high-elasticity chutes can be established. Double vertical high-elasticity chutes run through the whole building from top to bottom, and each spiral chute platform is provided with the entrance of vertical high-elasticity chute. Its overall design includes the vertical high-elasticity chute, the components supported by the chute and the intelligent detection

equipment of the vertical high-elasticity chute, as shown in Figure 8. In view of the fact that the vertical chute entrance and the spiral chute entrance are on the same platform, only one person can be evacuated in the chute at a time. In case of fire, once the detector in the building detects the change of fire-related parameters, it will trigger an alarm and jointly open the escape system of the vertical high-elasticity chute, so that the trapped people can quickly evacuate through the vertical high-elasticity chute under the action of gravity and friction.

3.2.1. Vertical High-Elasticity Chutes

The vertical high-elasticity chute includes two vertical escape passages. According to GB21976.4-2012 Equipment for Building Fire Escape and Shelter Part VI Building Fire Escape and Refuge Equipment Part IV: Escape Chute, the Materials with high elasticity, wear resistance and good shape recovery are applied in the vertical high elasticity chute, such as polymer rubber, polyester fiber, etc. After selecting a suitable vertical tube well, it is fixed in the vertical supporting pipeline, so that it keeps a certain speed decline under the action of extrusion friction and gravity pressure-resistant, wear-resistant and soft mats are set at the exit to reduce the impact force and ensure that people can be evacuated smoothly and leave safely and quickly.

3.2.2. Support Structure

The support construction of the vertical high-elasticity chute includes the support pipeline and the entrance platform. The strength, stability and safety of the vertical high-elasticity chute should be considered in the design, and then the evacuation safety of personnel can be guaranteed. The supporting pipes of the vertical high-elasticity chute are all made of stainless steel, and their inner diameter should correspond to the outer diameter of the hose to prevent it from falling off. The entrance platform and the spiral chute share the same platform in common, and the platform size should be able to meet the requirement that two evacuation modes can be performed simultaneously.

3.2.3. Intelligent Detection Equipment for Vertical High-Elasticity Chute

Intelligent Detection Equipment for Vertical High-elasticity Chute includes sensors located inside the chute, sensors located at the bottom of the chute and sensors located outside the chute. The types of sensors mainly include temperature sensor, gas sensor and pressure sensor, which can monitor the temperature change and oxygen concentration change in the vertical high-elasticity chute in real time during evacuation. The precise progress of evacuation is fed back by the pressure sensor at the bottom of the chute exit; The temperature and smoke detectors outside the chute are used to monitor the relevant fire parameters in the external environment in real time.

3.3. Flow of People for Vertical High-Elasticity Chutes

In order to ensure the safety of personnel evacuation, only one person is allowed

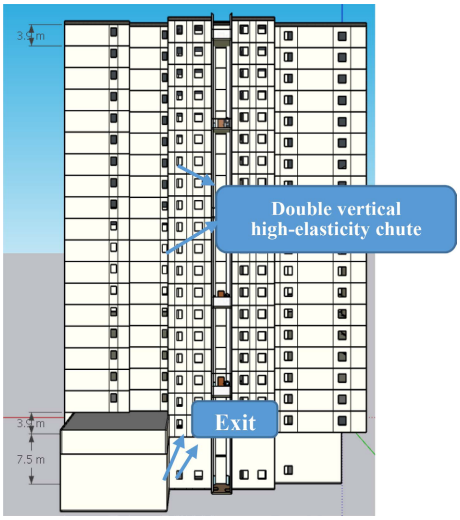


Figure 8. Model drawing of high elastic vertical and high elastic chutes for multi-storey and high-rise buildings.

to pass through the vertical high-elasticity chute at a time, and interception devices are equipped at each entrance. When someone is evacuated in the slide, the entrance will be closed soon. When the trapped person reaches the bottom, the pressure sensor will start to feed back the information to the control system, and the system will open the entrance in turn from the high floor to the low floor. If no one enters the vertical high-elasticity chute of a certain floor within 20 s, the control system will send feedback to the monitoring controller, who can switch the entrance remotely. Help buttons and walkie-talkies are equipped at each entrance for help communication in case of emergency.

4. Simulation Analysis of NECS Personnel Escape

4.1. Software for Escape Simulation

Pathfinder, escape simulation software developed by Thunderhead Engineering Company, USA, can digitally simulate the evacuation of people in a building and display it visually. In the process of calculation and solution, the software fully considers the relationship between people and buildings, and can set specific parameters for each independent person in the building and calculate their interaction, so it can get real and accurate simulation results. **Figure 9** and **Figure 10** are the interfaces of Pathfinder's Personnel Evacuation Analysis and Design and 3D Dynamic Output of Personnel Evacuation, respectively.

4.2. Model Parameter

The escape time (that is, the time required for safe evacuation TRSET) is influenced by many factors. In order to ensure the accuracy of the simulation results, it is necessary to analyze the values of relevant parameters before the simulation, and select the parameters that meet the actual situation of the building in combination with the analysis of the basic situation and service characteristics of the

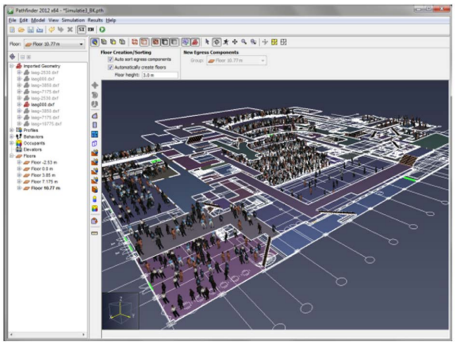


Figure 9. Personnel analysis and design interface of pathfinder.

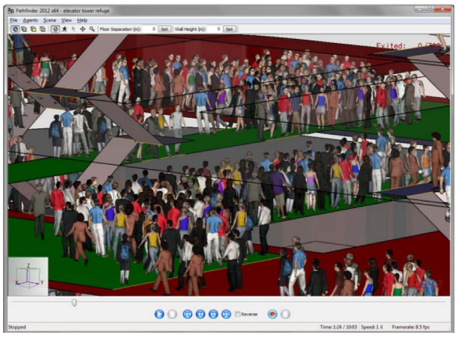


Figure 10. 3D dynamic output of personnel evacuation.

building. Escape time can be divided into the evacuation start time: T_{start} and the evacuation action time: T_{trav}, where the evacuation start time T_{start} represents the time from the fire time to the evacuation start.

The evacuation start time can be subdivided into three parts: detection time (T_{det}), alarm time (T_a) and personnel pre-action time (T_{pre}). Based on conservative considerations, it is suggested that T_{det} should be 60 s, T_a should be 180 s and T_{pre} should be 120 s.

In this paper, Pathfinder numerical simulation software is used to analyze the action time of personnel evacuation in multi-storey and high-rise buildings, and the action time is the time required for all personnel in the building to be evacuated to a safe area.

4.3. Setting of Simulation Parameters and Building Model

According to the drawings and related technical documents of a high-rise office building, a 20-story office building evacuation model is established, in which the standard height is 3.9 m and there are two evacuation staircases, and the number of people who can be evacuated is calculated by one person per 9 square meters according to the construction area. The calculation model is shown in Figure 11.

Through the preliminary simulation of only staircase evacuation in a 20-story office building, the time required for t (only staircase evacuation) can be obtained. Even in the most unfavorable situation of evacuation, the evacuation of

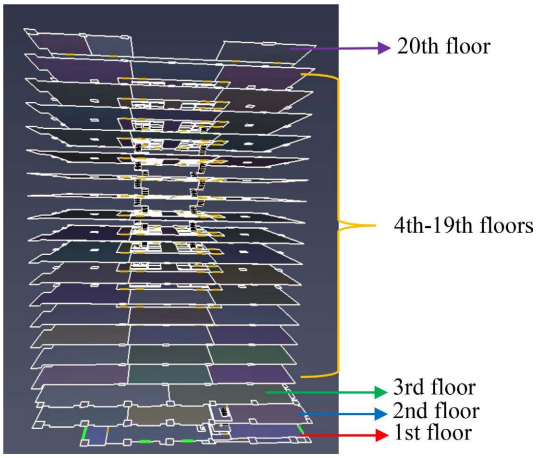


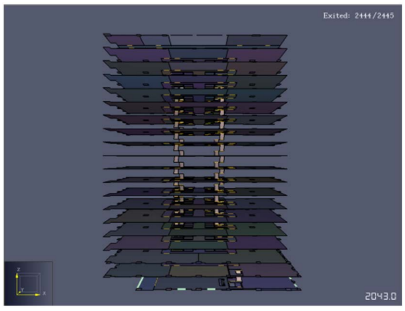
Figure 11. A full-scale model of a 20-story building.

personnel by spiral chutes and vertical high-elasticity chute start from the highest floor, under the efficient organization and leadership of evacuation, the number of people who can be evacuated by spiral chute and vertical high-elasticity chute in the same time is calculated. Considering that the evacuation efficiency is difficult to reach the ideal state in reality, the evacuation efficiency reduction factor (estimated value is 0.5) is set for spiral chute and vertical high-elasticity chute. According to the analysis of the design parameters of spiral chute and vertical high-elasticity chute, the number of people who can be evacuated through spiral chute and vertical high-elasticity chute in t time is about 292 and 71.

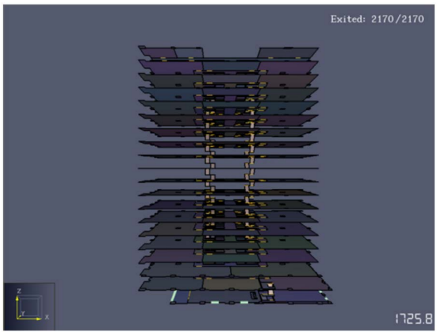
In view of the fact that the chute cannot be used for evacuation in Pathfinder, it is set in this simulation that once the evacuees arrive at the Exit of the chute, they will be judged to be safe, and the number of evacuees through the chute will be evenly distributed on each floor. After subtracting the number of people evacuated through the chute on each floor, the number of people in the building by the simulation is as follows: when evacuating through the staircase, the number of people is 2445, when evacuating through the double spiral chute and staircase, the number of people is 2153, and when evacuating through the NECS and staircase, the number of people is 2082.

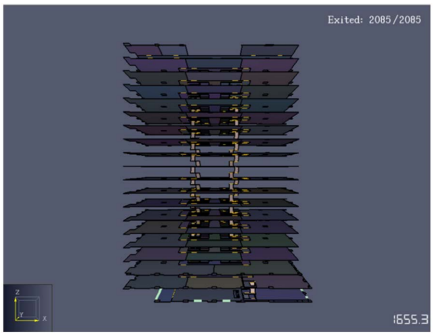
4.4. Simulation Analysis of Personnel Escape

The results of personnel escape simulation are shown in **Figure 12** and **Table 1**. Under the different evacuation modes, by comparing the escape time, it is found that the evacuation mode of NECS cooperating with the staircase can effectively shorten the escape time (from 2043 s to 1655.3 s, a decrease of about 19%) of people in high-rise buildings. By comparing the density distribution of people under different evacuation modes in **Figure 13**, it is found that there will be congestion in the staircase during the evacuation process, and the evacuation mode of chutes cooperating with staircase can alleviate the congestion in the staircase to some extent.



(a)

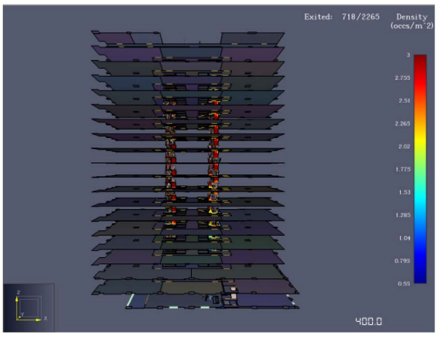


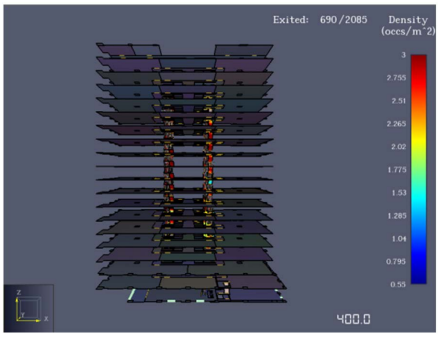


(b) (c)

Figure 12. Results of personnel evacuation simulation for 20-storey office building. (a) Stair evacuation; (b) Coordinated evacuation of double spiral chutes and staircase; (c) NECS coordinated staircase evacuation.

(a)





(b) (c)

Figure 13. Distribution of Personnel Density in 400 s, Escape Simulation of 20-story Office Building. (a) Stair evacuation; (b) Coordinated evacuation of double spiral chutes and staircase; (c) NECS coordinated staircase evacuation.

Table 1. Simulation results of personnel escape under different evacuation forms in a 20-story office building.

Simulated working condition	Escape time(s)
Only staircase for evacuation	2043
Coordinated evacuation of double spiral chutes and staircase	1726
NECS coordinated staircase evacuation	1655

5. Conclusion

Based on the existing research results and long-term exploration on the evacuation form of multi-storey and high-rise buildings, the author puts forward a NECS composed of "Double Spiral Chutes and Double Vertical High-elasticity Chutes", and makes a preliminary design of its various components (chute, support structure, intelligent detection equipment, the crowd and etc.). In addition, the special software was applied to simulate the whole process of evacuation and escape in multi-storey and high-rise buildings, and the evacuation efficiency of staircase evacuation mode and chute-staircase evacuation mode was compared and analyzed. The evacuation time of people can be effectively shortened (by about 19%) by using NECS coordinated staircase evacuation, and the congestion of stairs can be alleviated, which verifies the effectiveness of NECS in evacuating the crowd.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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