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Evacuation Simulation in a Cultural Asset Fire: Impact of Fire Emergency Evacuation Facilities for People with Disabilities on Evacuation Time

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Abstract: More cautious fire safety evacuation assessment and escape route assistance are required when people with disabilities encounter a fire hazard in a historical museum. This study uses the old Chiayi City Hall, which is mainly used for an exhibition space, as the example. The core of this study is the problem of fire evacuation that emerged after the historic building opened and was reused as a museum; it uses Pathfinder evacuation simulation software, discussing the difference between traditional and segregated evacuation and assuming the original evacuation, elevator emergency evacuation, and external ramp evaluation. There are three evacuation scenarios, and the number of accommodated people is set to 730, pursuant to the applicable law. Comparing the conditions of people with disabilities and ordinary members of the public during evacuation through the foregoing three scenarios, the overall evacuation time and survival rate of the original evacuation scenario are 440 s and 49.8%, respectively; and the overall evacuation time and survival rate of the barrier-free elevator emergency evacuation scenario are 332 s and 65.4%, respectively; the overall evacuation time and survival rate of the external ramp evaluation scenario are 320 s and 65.6%, respectively. The computer data analysis shows that the use of the external ramp evaluation gives people with disabilities the best evacuation time and survival rate because the architectural form of cultural heritage buildings is more fragile, specific, and fast-burning than that of ordinary buildings. As the global awareness of cultural asset preservation and revitalization is increasing, the evacuation of people with disabilities in the building in the case of fire is very important. The results of this study can be used as an emergency evacuation design recommendation for people with disabilities in the cultural assets through evacuation simulation analysis.

Keywords: historical museum building; crowd simulation; evacuation time; fire safety; computer simulation

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1. Introduction

Large areas of historical buildings are revitalized and reused as art exhibition spaces as well as commercial buildings to attract more users. In this study, we studied this type of building, aiming to investigate how people with disabilities could secure their safety in the case of fire when they were working, visiting, and exhibiting their work in these historical buildings. These traditional buildings are only equipped with stairs and hallways for cross-sectional evacuation facilities. People with disabilities required assistance from surrounding people during fire evacuation, resulting in a delayed evacuation time. The optimal evacuation model for people with disabilities is used as the basis for the personnel control and architectural planning for the future museum fire protection and evacuation design. Many cultural heritage buildings do not take the corresponding measures for traffic flow planning and escape equipment for people with disabilities. The main refuge and the escape equipment most commonly seen are slow descending machines and stairs, and very few historical sites have specific elevators for people with disabilities to use. However, it is necessary to discuss the nature and type of personnel and the internal space planning. Thus, this research aims to explore the best evacuation mode and the number of occupants.

In recent years, the concept of the reuse of historical sites and buildings has become the most important topic and trend in the world, the number of people in a museum is the number of people that can be accommodated by dividing the open space area by three square meters. For historic buildings, this number is a serious challenge to fire evacuation.

Reported that in developed countries the protection of historical sites and buildings has been widely implemented, and the outcomes of the relevant policies are quite decent. However, historic buildings use more wooden construction materials. In addition to the need to avoid fires through fireproof materials, the evacuation behavior of people should also be considered [1]. Calculated that the actual fire resistance and the classes of fire risk for load-bearing timber structures based on Russian national standards were compared with the fire design methods based on the European norm [2].

Novel discrete molecular dynamics technique to simulate the evacuation of agents in panic situations. Various adaptive geometric configurations were analyzed for improved crowd flow [3]. Two types of case studies to investigate refuge preferences in public buildings: observational case studies (OCS) and simulated case studies (SCS). Related survey results show that "distance" and "familiarity" are the two most important factors for evacuation in public buildings [4].

Stated that since the safety of the occupants during evacuation is always the top priority, and their behavior has a huge impact on their safety, more investigations of human behavior under fire conditions are needed, especially on how evacuation instructions are customized for each occupant's situation (for maximum impact) and can be provided to users in the event of a fire [5]. Stated that the occupant behavior in a fire emergency is still unpredictable, and there is no reliable occupant behavior and decision-making model [6]. Stated that a decision-making model in a fire situation includes factors such as people's consciousness, beliefs, attitudes, motivations, and coping strategies [7].

Used Pathfinder (agent-based evacuation simulation software) to simulate the evacuation from a high-rise residential building. The simulation results show that allowing elevators to be used for the benefit of disabled occupants may cause able-bodied occupants to misuse the elevator; no matter how crowded, evacuees will try to use the first visible exit point [8]. People of different health categories have different evacuation times when using stairs and specific elevators [9].

The changes in internal space planning and the traffic flow of historical sites and buildings probably cause the public psychological symptom of panic and helplessness during an evacuation, which makes them choose the wrong escape route or evacuation method.

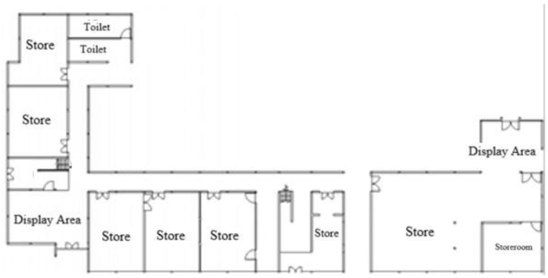
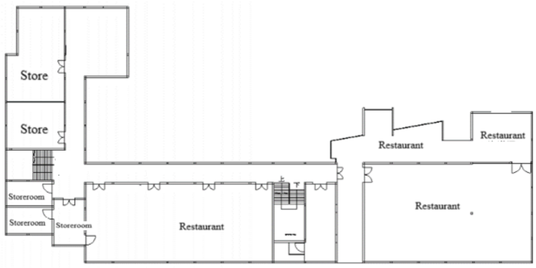
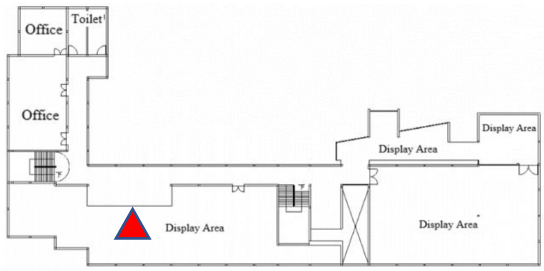
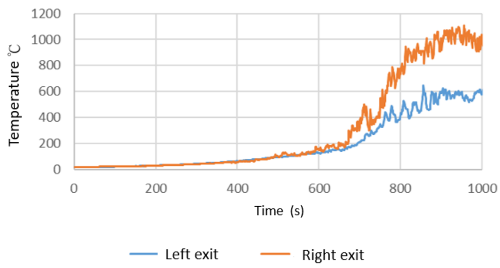
2. Research Methods

2.1. Study Field

The study field is the old Chiayi City Hall, jointly used by the city hall and the city council in the early days. The old Chiayi City Hall adopted an asymmetrical design, breaking with the traditional symmetrical architectural design of the past. The plan is L-shaped, with three entrances and exits; the building space is made transparent with the use of glass, openings, corridors, and so on.

The space configuration used by people with disabilities is open. The first-floor configuration is mainly planned for the commercial space, exhibition space, and service center; the second floor is the historical and cultural relic exhibition hall, restaurant, and souvenir shop; the rest comprises the youngster start-up workspace, the exhibition, and the lecture hall. The third floor of the building will be constructed using modern construction methods after removing the walls and roof covering. The space is planned for the exhibition, a semi-outdoor platform, and rest use, as shown in Table 1. We assumed that the fire source was located in the exhibition room on the third floor. The fire was caused by a power break that ignited the wood finishing materials. After the fire, the ambient temperature distribution between the left and right emergency exits of the historic building posed a considerable hazard to the people with disabilities. As historical sites and buildings need to be refurbished in the building space and facilities before being converted to being open for use, a lot of electrical equipment should be added. Therefore, well-designed evacuation routes and evacuation strategies can not only reduce personnel casualties during disasters, but also greatly increase the survival rate.

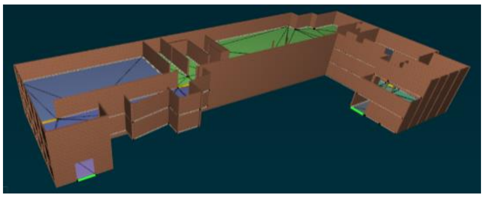
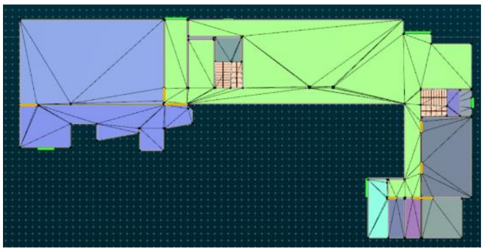
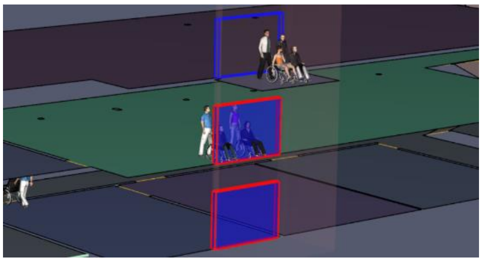
Table 1. Distribution of primary uses of each floor.

Distribution of Main Uses of Each Floor	
First Floor	
Second Floor	
Third Floor (▲: Fire source location)	
Emergency exit temperature during fire	
Exterior View (Source: Chiayi City Cultural Bureau)	

2.2. Research Instrument

This study used Pathfinder software (license code: 60803F8D841ED910108946). The building model of the research object has 8 exits on the first floor and 2 staircases and the floor area is 1039 m^2. There are 2 staircases on the second floor, and the floor area is 1077 m^2; there are 2 staircases on the third floor, and the floor area is 1053 m^2. The total floor area of the building is 3164 m^2. The compartments, the shortest evacuation traffic flow, the entrances and exits, the stairs, the elevators, etc., are built according to the usage pattern of each floor, as shown in Table 2.

Table 2. Model setting.

Model and Settings	
3D Model	
Shortest Evacuation Traffic Flow	
Exit Settings	
Stairs Settings	
Elevator Settings	

2.3. Evacuation Behaviors

The visibility of fire evacuees trapped in the smoke will gradually decrease; because the composition of the smoke is inconsistent and the size varies, visibility in the smoke is more difficult than visibility in the fog, and the attempt to determine the escape route and the evacuation decision time will be extended. The hazards of fire include temperature, smoke toxicity, radiation heat intensity, and smoke height as shown in Table 3.

Table 3. Fire hazard indicators for human tolerance (organized in this study).

Hazard Scenario.		Human Tolerance Limits			
		BSI	SFPE	NFPA 130	Takeyoshi Tanaka
Smoke Height		--	--	≧1.8 m	≧1.8 m
Fire Temperature		≦60 °C	≦65 °C	≦60 °C	45 °C pain
Smoke Toxicity	CO	≦1400 ppm	≦1400 ppm	≦1500 ppm	≦1200 ppm
	CO_2	≦6%	≦5%	--	<20%
	O_2	≧12%	≧12%	--	≧12%
	HCN	--	≦80 ppm	--	<270 ppm
Visibility		≧2 m	--	≧10 m	--
Heat Radiation Strength		≦2.5 kW/m^2	≦2.5 kW/m^2	≦6.3 kW/m^2	≦4 kW/m^2 pain within 10 s

2.4. Parameter Setting

The walking speed declines sharply at the after the age of 63. The walking speed for people between 14 and 64 years old is 1.25 m/s, approximately, and the walking speed for people over 65 is 0.97 m/s, approximately, and even lower [10]. Mentions that the average speed of a wheelchair is about 0.28 m/s. If it is moved by an escort, the speed is about 0.55 m/s. The number of accommodated people in the building is in accordance with the local laws and regulations (provisions of Article 157 of the "Standard for Installation of Fire Safety Equipment Based on Use and Occupancy"), and the calculation of the number of accommodated people is reviewed based on the historical site's opening and reuse, which are the most commonly seen. In this study, the accommodation of people in exhibition halls, shopping malls, and restaurants is shown in Table 4. After calculating from the table below, the maximum number of accommodated people is 260 on the first floor, 220 on the second floor, and 250 on the third floor. The total number is therefore 730.

Table 4. Personnel parameter setting.

Title	Parameter Setting
Total Number of Simulated People	730
Edit Profile	Young Adult (30 y): 1.4 m/s, 1.8 m Child (14 y): 1.25 m/s, 1.46 m Elderly Person (65 y): 0.6 m/s, 1.7 m
Wheelchair	Specification: 2.15 m^2 Speed: 0.55 m/s
Elevators	Specification: 4.8 m^2 Speed: 2.5 m/s
Fixed Number of Seats in the Restaurant	Specification: 0.5 m^2 Quantity: 240

Table 4. *Cont.*

Title	Parameter Setting
Occupants	Total Number (1st Floor): 260 Staff Members: 7 Young Adults (30 y): 90 Children (14 y):80 Elderly People (65 y): 80 Wheelchairs: 5 Assistants: 5
	Total Number (2nd Floor): 220 Staff Members: 6 Young Adults (30 y): 80 Children (14 y): 70 Elderly People (65 y): 60 Wheelchairs: 5 Assistants: 5
	Total Number (3rd Floor): 250 Staff Members: 4 Young Adults (30 y): 90 Children (14 y): 80 Elderly People (65 y): 70 Wheelchairs: 5 Assistants: 5
Behaviors	Go to Exit Assist Wait for Assist Go to (00,00,00) m Wait (0.0) s

2.5. Limitations and Assumptions in the Study

According to Taiwan's fire protection laws, the number of people in a museum is the number of people that can be accommodated by dividing the open space area by three square meters. For historic buildings, this number is a serious challenge to fire evacuation. The fire source is assumed to be next to ladder B of the third floor [11]. At the time of 148 s after the fire occurs, the average temperature of the fire floor (the third floor) is 65 °C, as shown in Figure 1. Research collects a lot of information pertaining to the studies on the human body's smoke and heat hazard determination standards, among which 65 °C is the maximum temperature at which humans can survive in the fire ground (Figure 1) [12]. Therefore, it is seen from the foregoing that the final allowable evacuation time for the fire floor (the third floor) of the building is 148 s, which is used as the standard for the subsequent simulation scenario hypothesis. Assuming that the fire starts next to ladder B of the second floor, at the same number of seconds of time ladders A and B of the second and the third floors cannot be used, and the evacuees will be trapped or killed. Likewise, the same will subsequently occur if it happens on the first floor.

This study assumes three different scenarios for the evacuation simulation of the building model; the scenarios are all large-scale arts and cultural activities (National Cultural Heritage Day), and the evacuees in the three scenarios are simulated by using the same data. Scenario A is the most primitive situation, and elevators A and B are available for the evacuees and people with disabilities to simulate, as shown in Figure 2. In Scenario B, in order to avoid collisions, pushing, and other factors affecting the overall evacuation time between the people with disabilities and the other evacuees, a barrier-free elevator is added for people with disabilities to carry out a segregated evacuation, while elevators A and B are used by the other evacuees, as shown in Figure 3. In Scenario C, the barrier-free elevator is changed to an external ramp, as shown in Figure 4. Through the foregoing three scenarios, you can compare the evacuation status of each scenario and verify the best allowable evacuation time for each scenario when a fire occurs, thereby achieving the effect of reducing casualties.

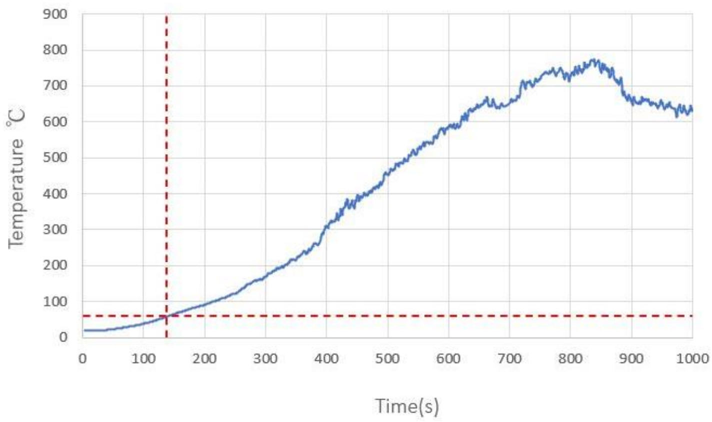


Figure 1. Curve of average temperature data on the third floor.

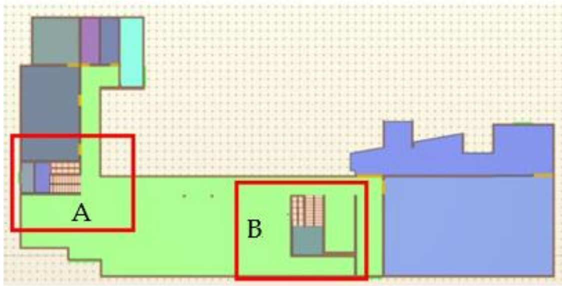


Figure 2. Ladders A and B configuration diagram in Scenario A.

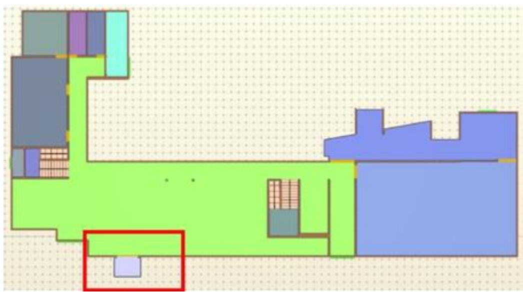


Figure 3. Independent power supply elevator configuration diagram in Scenario B.

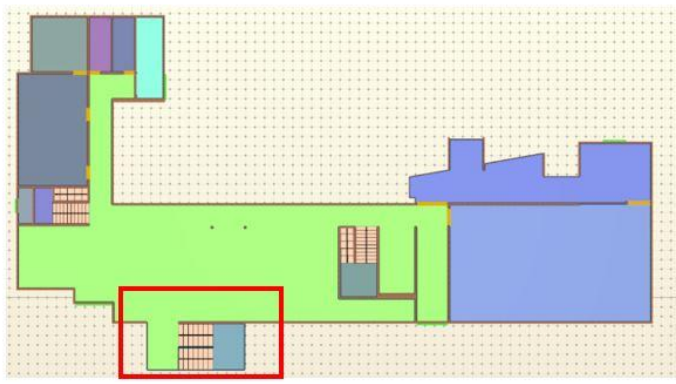


Figure 4. External ramp evaluation configuration diagram in Scenario C.

3. Results

3.1. Scenario A: Original Evacuation Scenario

This scenario is the initial setting condition. When a fire occurs, people with disabilities are given priority to evacuate as soon as possible; as people with disabilities are slow, the rear evacuation crowd is congested, as shown in Figure 5. As a result, 139 evacuees on the third floor are unable to escape from the fire, which affects the overall evacuation time. By 329 s after the fire, the evacuees, staff members, and the people with disabilities on the fire floor (the third floor) have successfully evacuated. The overall evacuation time of the building is 440 s. In 285 s after the fire breaks out, all the people with disabilities escape safely from the building. Three hundred and sixty-four people successfully evacuate in 148 s on each floor, and 366 people are trapped, as shown in Figure 6.

Figure 5. Original evacuation situation map.

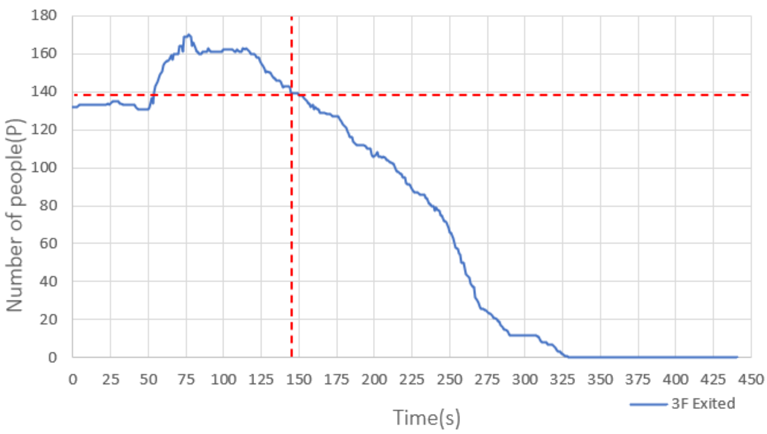


Figure 6. Front room of the escape ladder on the third floor at the 148th second.

3.2. Scenario B: Evacuation Scenario of Barrier-Free Elevator

In addition to the same set of values and space use as Scenario A, an additional barrier-free elevator is installed in this scenario. The staff member guides the people with disabilities to evacuate to the elevator as soon as the fire breaks out but encounters the ongoing evacuees on the way to the elevator. They must slow down or even stay to wait for the people to evacuate, as shown in Figure 7. In addition, at the 148th second, there are 30 trapped people on the third floor, and some of the evacuees and the people with disabilities cannot be completely evacuated to the outdoors or cannot even leave the elevator. By 199 s after the fire occurs, the evacuees, the staff members, and the people with disabilities on the fire floor (the third floor) have successfully evacuated. The evacuation time of the whole building is 332 s, and 328 s after the fire breaks out, all the people with disabilities safely escape from the building. The number of people on each floor successfully evacuated is 477 in 148 s. Two hundred and fifty-three people are trapped, as shown in Figure 8.

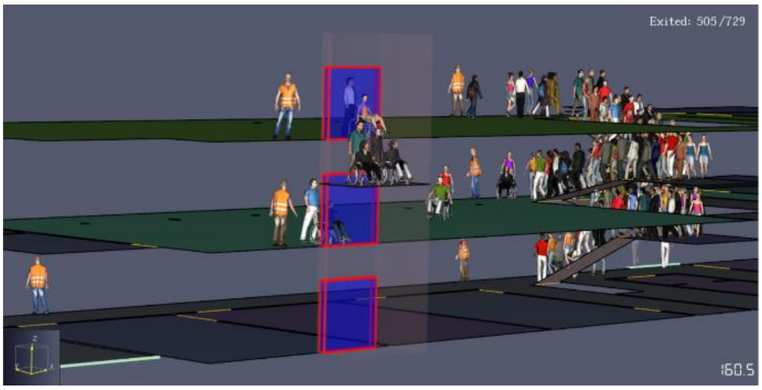


Figure 7. Evacuation situation diagram of barrier-free elevator.

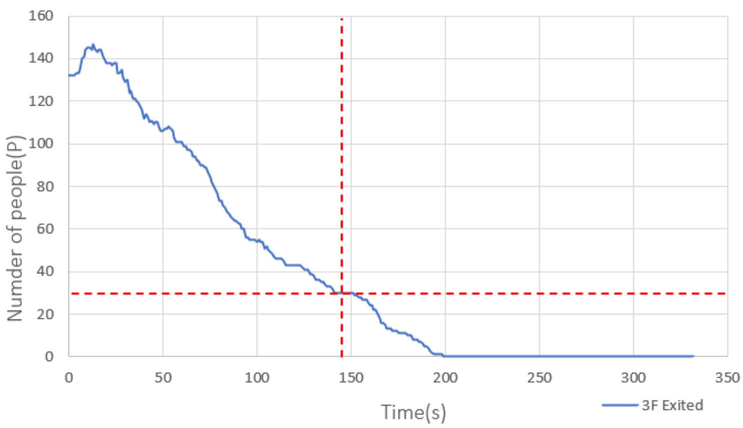


Figure 8. Front room of the escape ladder on the third floor at the 148th second.

3.3. Scenario C: External Ramp Evacuation Scenario

All the condition settings of Scenario C are roughly the same as the previous two scenarios. The difference is that the barrier-free elevator in Scenario B is changed to an external ramp, as shown in Figure 9. In Scenario B, the people with disabilities must take the elevator to the first floor and leave the building through the internal exit. In this situation, they can directly use the independent exit of the ramp to escape, which prevents people with disabilities from having to enter and exit the fire ground more than once. It not only reduces the occurrence of accidents, but also increases the survival rate a lot.

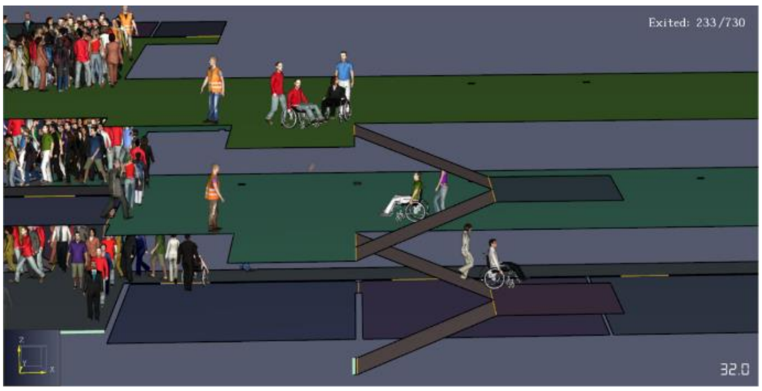


Figure 9. Evacuation situation diagram of external ramp.

One hundred and forty-eight seconds after the fire broke out, 16 people are trapped on the third floor, as shown in Figure 10. At the 186th second, the evacuees, the staff members, and the people with disabilities on the fire floor (the third floor) have successfully evacuated from the building. The evacuation time of the whole building is 320 s, and 230 s after the fire breaks out, all the people with disabilities safely escape from the building.

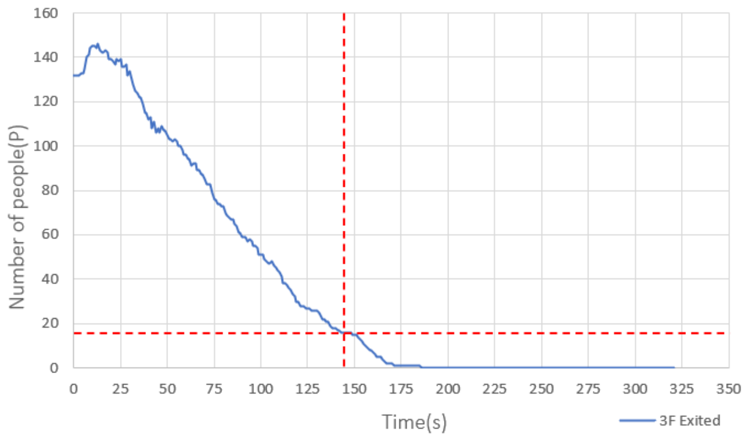


Figure 10. Front room of the escape ladder on the third floor at the 148th second.

3.4. Comparison of Simulation Scenarios

Scenario A: In the early stage of the fire, the traditional escape ladder gave priority to the people with disabilities to evacuate but caused the general crowds to be congested or even stagnated during evacuation, which caused 139 evacuees on the third floor to be trapped, while the people with disabilities were trapped at the 285th second and all were evacuated from the building in 285 s. In reality, due to the fear of the fire, the general public probably wanted to overtake the people in front, which might have caused more casualties. According to the foregoing, such simulation makes people with disabilities evacuate successfully, but it reduces the evacuation speed of the general public and indirectly causes panic and puts psychological pressure on the evacuees, which directly affects the overall evacuation time and the number of evacuees.

Scenario B: Using barrier-free elevators for the people with disabilities to evacuate and carrying out segregated evacuation with the general public not only allows the people with disabilities to use independent evacuation routes, but also avoids affecting the general public's evacuation time and the entire evacuation due to the speed of the people with disabilities, thus not causing crowding, congestion, etc., during evacuation. Compared with Scenario A, although it takes longer for the people with disabilities to escape from the building, it greatly reduces the number of people trapped in the fire ground. Therefore, despite the fact that Scenario B makes the people with disabilities and other the evacuees carry out segregated evacuation, the people with disabilities must spend a longer time for evacuation because of the elevator waiting time. The advantage is that the general public will not be affected by the people with disabilities during the evacuation, and this will achieve the effect of reducing the overall evacuation time and improving the survival rate of the evacuees.

Scenario C: Although the results are not much different from those of Scenario B, the details of the evacuation are entirely different. Scenario C uses external ramps for the people with disabilities to evacuate. In contrast, this provides a more comfortable and larger evacuation space. The escape route is the same as the segregated evacuation concept of Scenario B. Independent exits are set for the people with disabilities to avoid encountering the fire ground again. This reduces the risk of fire and makes them directly escape from the building, which is important for the overall evacuation. The comparison of the foregoing three simulation scenarios is shown in Table 5 and Figures 11 and 12. People with disabilities are passive in terms of their evacuation behaviors as they have to rely on the help of people around them to escape from the fire environment. Scenario B and Scenario C construct a facility where people with disabilities can evacuate on their own and with the assistance of the surrounding personnel so that the efficiency of evacuation in the case of fire is better than that using traditional elevators. Therefore, Scenario B needs to meet the following requirements: the elevator is located outdoors; the elevator waiting space is protected by an independent fire prevention structure; the elevator is protected by an independent emergency power supply; and the elevator control logic is programmed to effectively perform the evacuation. The elevator control logic should be connected to the fire alarm system, and the evacuation should be prioritized from the fire floor. The combination of Scenario B and Scenario C could be the best design for the restoration of cultural assets according to the environment and available space.

Table 5. Comparison of data in various simulation scenario.

Scenario Simulation	Overall (730 People) Evacuation Time (Seconds)	3rd Floor (250 People) Evacuation Time (Seconds)	Number of People Successfully Evacuated in 148 s	Number of People Trapped in 148 s	Advised Maximum Number of Accommodated People
Traditional Escape Ladder	440	329	364	366	364
Barrier-Free Elevator	332	199	477	253	477
External Ramp	320	186	479	251	479

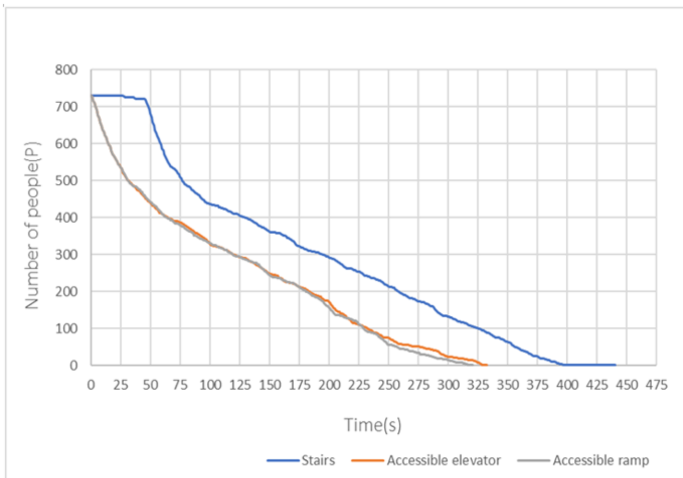


Figure 11. Comparison of data in various simulation scenarios.

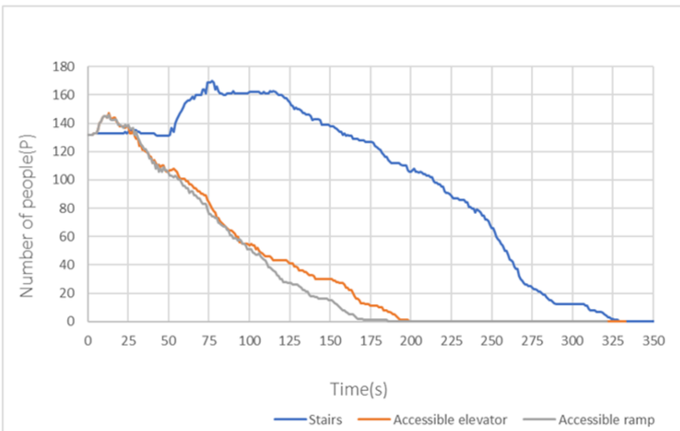


Figure 12. Comparison of the number of people in the front room of each evacuation ladder on the third floor.

In addition, if the venue accommodates 730 people according to the reasonable number of people, after the cross-analysis of the fire simulation results and the allowed evacuation time, the evacuation of all the people needs to be completed within 148 s, which will result in at least 250 casualties according to the three analysis results. In addition to improving the loss of the traditional evacuation scenario through the revision of the evacuation scenario, the number of people allowed to evacuate the cultural assets should also be controlled. The analysis results show that if outdoor ramp access is provided, the optimal number of people allowed should not exceed 479.

4. Conclusions and Recommendations

4.1. Conclusions

In recent years, the awareness of the preservation of historical sites and buildings has increased. Many countries have begun to emphasize the preservation and reuse of cultural heritage buildings. This study simulates the evacuation of cultural heritage buildings in the face of fire when they are open and reused, assuming three simulated scenarios and discussing the situations of people with disabilities in the evacuations in the scenarios, as well as analyzing the following points:

1. Extract the evacuation density graphs from the software. The advised maximum number of accommodated people is 364.
2. The use of traditional escape ladders enables people with disabilities to evacuate first, but simultaneously, it causes the congestion and stagnation of evacuees on the fire floor. Compared with the other two ways, the evacuation efficiency is the worst among the three.
3. Barrier-free elevators are used for segregated evacuation, but at the time of 148 s, some disabled people have not yet escaped from the building in 148 s or have not even left the elevator. Compared with scenario A, the effect is very significant in evacuation and congestion resolution.
4. External ramps will be used, which not only shortens the evacuation time but also brings better evacuation routes for people with disabilities, reducing the overall evacuation time and effectively improving the survival rate of people with disabilities and the evacuees. Compared to the other two, this simulation is the most ideal evacuation approach.
5. When simulating the three evacuation scenarios, it is found that the slow speed of people with disabilities causes the initial crowd congestion or stagnation and such a problem directly affects the psychological level of the evacuees, causing group panic and an even larger number of casualties.
6. The number of people in the three simulation scenarios is set in accordance with the Standard for Installation of Fire Safety Equipment Based on Use and Occupancy. The number of occupants is 730. The results show that the survival rates of the three simulation results are 49.8%, 65.4%, and 65.6%, and the numbers of occupants and survivors are relative numbers. If we want to increase the survival rate, we have to reduce the number of accommodated people. Therefore, the calculation should be based on the structures of cultural heritage buildings and the fire hazards, usage patterns, and allowable evacuation time. It is not the same as that of ordinary buildings. The current fire protection regulations shall be used to calculate the number of accommodated people.

4.2. Recommendations

As most of Taiwan's historical sites and buildings are made of wood, and with the rise of the opening and the reuse of cultural heritage buildings and the government's emphasis on people with disabilities, the fire safety issue and evacuation have certainly become important. Thus, the results of the study show that the following suggestions are sorted out after analysis:

1. Add a special refuge and escape equipment for people with disabilities when planning the evacuation in cultural heritage buildings in the future.
2. It is advised that the staff members should introduce the internal space planning and environment to the tourists before visiting to ensure that every tourist understands the evacuation route.
3. It is advised that employees regularly implement disaster prevention education and training, and they should familiarize themselves with the evacuation routes and emergency situations when a fire occurs by means of actual drills.
4. It is recommended to use firefighting equipment such as smoke alarms, detectors, and an alarm system to assist the evacuees in detecting a fire as soon as possible in order to evacuate as soon as possible, thereby improving the overall escape efficiency.
5. Adding fire-resistant coatings to building structures can effectively improve the evacuation results.
6. People with disabilities will be affected by other people at the beginning of the fire, which increases the overall evacuation time and reduces the efficiency of escape. This is understandable. We will continue to collect research data from related scholars and develop this issue in the future.

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