EVACUATION AND SMOKE MOVEMENT INTERACTIVE SIMULATION MODEL

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ABSTRACT

The evacuation and smoke movement interactive simulation model has been developed to handle the evacuation of large populations of individuals with mixed abilities. The advantages of the model are: 1) to handle evacuation of individual evacuees considering variety of behavioral parameters, 2) to handle total evacuation in a multi-story building via the stairs, 3) to consider interactions between egress behavior and spread of smoke in a building. The system is a deterministic simulation program implemented by the agent-based computer language, Repast. The evacuation model consists of three sub-models; space model, human model and smoke model. Some case studies were conducted to verify validity of the model. It was confirmed that the calculated flow rate or density of a crowd almost agreed with the previously measured ones and the evacuation behavior under the smoke movement can be represented by the model.

KEYWORDS: Evacuation, Simulation, Smoke movement, Interactive model

INTRODUCTION

Large buildings such as high-rises and commercial complexes present a risk of evacuating all the occupants during a fire taking a long time as seen in the explosion of the World Trade Center in 1993[1]. Larger buildings accommodate more occupants. Then, a wide variety of people behave differently during emergency escape according to their age and physical capacity. To predict behavior in evacuation under such conditions, modeling the behavior of individuals according to their properties is necessary. Exodus[2], Simulex[3] and other models are presently available for predicting individual behavior in evacuation. The authors have developed calculation models for predicting the evacuation of occupants who exhibit varying escape patterns[4,5]. One important aspect of predicting evacuation throughout a large building is the modeling of occupants' behavior in staircases. The previously developed models have failed to accurately model the space in staircases or the evacuation therein. The prediction results therefore could not sufficiently represent actual behavior.

The authors have fully reviewed calculation algorithms mainly for the evacuation model in staircases. This paper describes a method for modeling evacuation, and provides case studies of evacuation throughout the building and the results of validity evaluation of the calculation model. Also reported are the results of application of the model to a fire of a retail store that occurred in Japan as an example of behavior prediction during a fire. The evacuation model that the authors have developed is intended not to accurately reproduce the behavior in evacuation during a fire but exclusively for use as a tool for verifying the safety of facilities in the building design phase.

DESCRIPTION OF EVACUATION MODEL

The evacuation model is based on the escape model during a building fire that the authors developed[4, 5]. Individual behavior in evacuation is represented using Repast, an agent -based simulation toolkit. The model is composed of three sub-models as shown in Fig. 1. Improvements over existing evacuation models are described below.

- Walking on slopes at given angles has been formulated to model walking in the staircase.
- Obstacles to walking in the room such as furnishings and the behavior to get around them have been modeled.
- Selecting the destination based on the congestion around it has been made possible.
- Reproducing the stay of the evacuee in the space designated as the final area of refuge has been made possible.

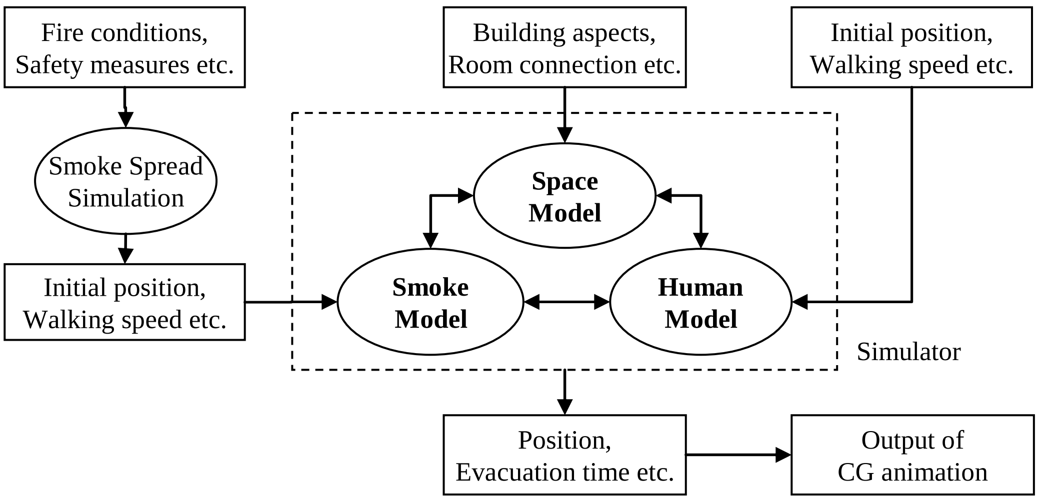


FIGURE 1. Composition of the simulation model

Space Model

The space model is a model of each space constituting the building for predicting evacuation. A building is regarded as an aggregate of rooms and passageways that are virtual spaces enclosed by openings and walls. Fig. 2 shows the concept of modeling space in a building. No space is discretized with meshes or networks to provide a continuous area. Enclosed spaces are connected to each other via openings to model all the spaces in the building.

Enclosed spaces including rooms, base units of the space model, can be divided into several areas. The angle and direction of slope of the floor can be separately specified in each area using gradient vectors. Thus, staircases and spaces with sloped floor in the building are modeled.

Fig. 3 shows the concept of modeling space in staircase. Staircases are connected to multiple floors via landing. No staircases are therefore modeled as one room from the first floor to the top floor. Each story is modeled as a base unit of the staircase. Multiple stories are connected to one another via virtual openings. In existing models, staircases are regarded as passageways without any slope and the walking in the staircase is simulated by giving the walking speed. No effects of evacuees taking a spiral course via landing can therefore be taken into consideration. A staircase in a story, a base unit, is divided into four cells, two landings and two flights, which are connected to each other via virtual openings. Flights are modeled as slopes, and the slope angle and direction of the floor are given using unit gradient vectors. In the space in each cell, the evacuee specifies the opening between the landing and the flight as the destination. All the spaces in a multi-storied building are reproduced by connecting stories via staircase.

Obstacles to escape in the building such as furnishings and equipment can be placed anywhere in the room. Two types of obstacles can be modeled separately.

a) Low desks or other obstacles that prevent the evacuee from passing over them but allow the evacuee to obtain information on the destination or other evacuees behind them.
b) Walls or other obstacles that prevent the evacuee from passing through them and do not allow the evacuee to obtain any visual information behind them.

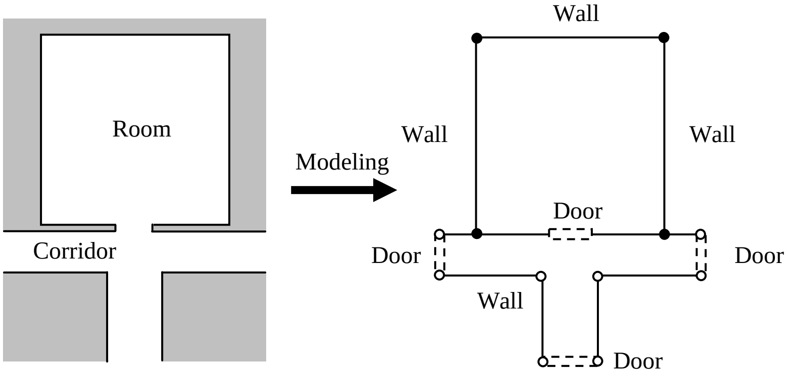


FIGURE 2. Concept of modeling of space

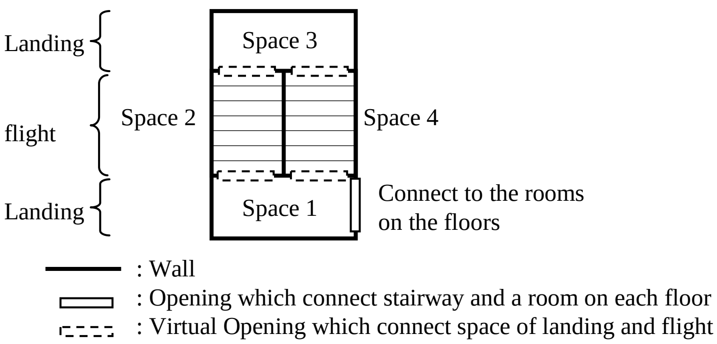


FIGURE 3. Modeling of space in staircase

Human Model

In the human model, behavioral parameters of the evacuee are controlled and the destination of each evacuee, and the direction and target of movement are determined. The area occupied by the evacuee is modeled as a circle with the diameter identical to the shoulder length of the occupant.

Behavioral parameters in evacuation such as the walking speed, selection of escape route and the need of help during escape can be set arbitrarily for each evacuee. Evacuees are classified into four categories according to the characteristics of selection of escape route.

- Type I: Decides the direction of movement arbitrarily based on the information available in the room
- Type II: Has a full knowledge about the escape routes in the building and decides the direction of movement arbitrarily
- Type III: Follows instructions given by emergency evacuation light
- Type IV: Follows other evacuees

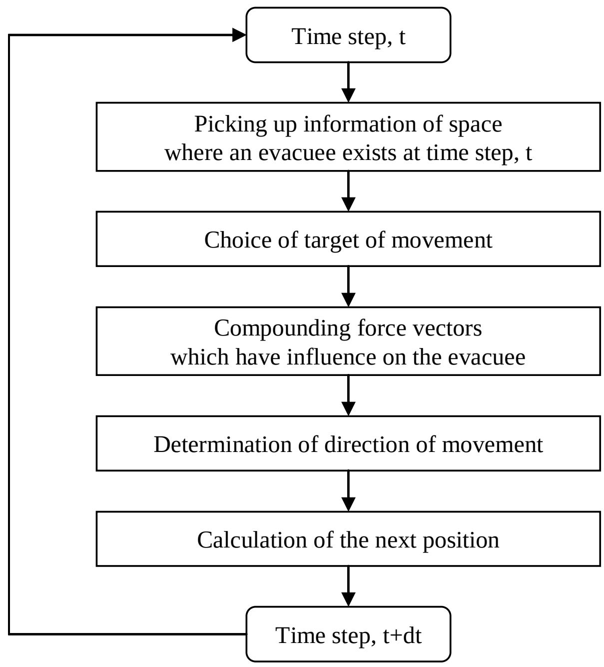


FIGURE 4. Flowchart of steps for evacuee to determine the target of movement

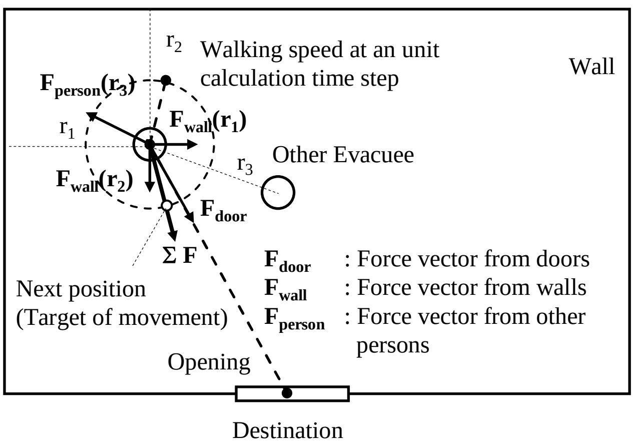


FIGURE 5. How the evacuee determines the direction and target of movement

A flowchart of steps that the evacuee follows to determine the target of movement is shown in Fig. 4. When predicting behavior in evacuation, it is assumed that the evacuee first selects the destination based on the position information at the specific point of time and determines the direction and target of movement according to the destination. Two types of destinations have been defined.

- Long-term destination: Place where the evacuee wants to take area of refuge finally.
- Short-term destination: Immediate destination such as the exit or emergency evacuation light before finally reaching the long-term destination.

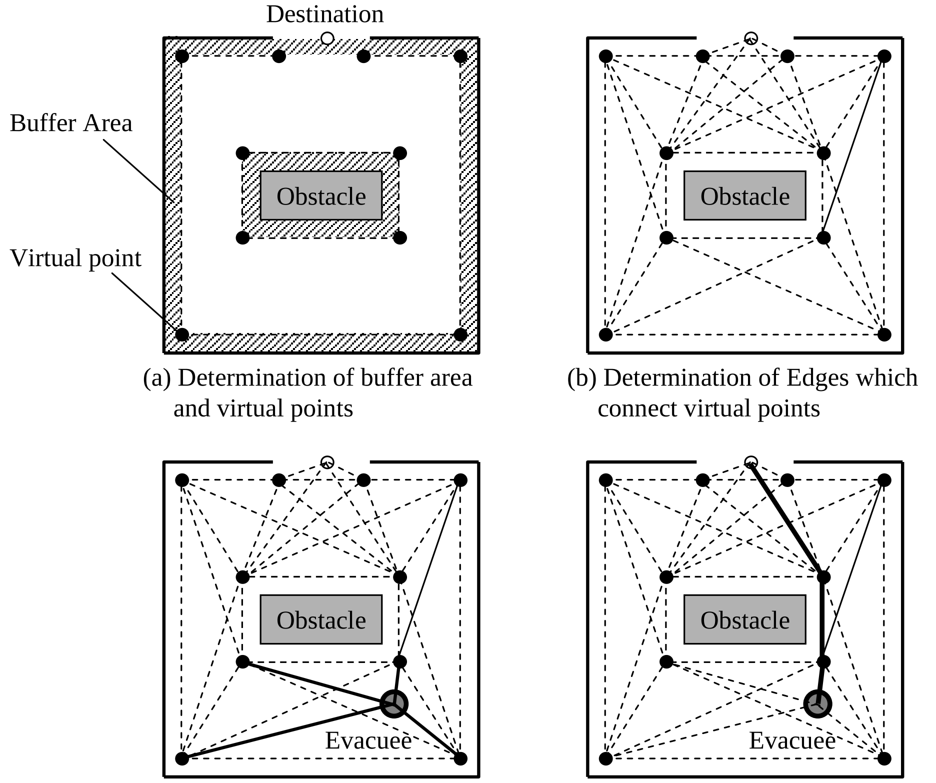
The evacuee continues escape while selecting short-term destinations to finally reach the long-term destination. The evacuee is not advised of the location of the long-term destination at the start of escape. Destinations are a) final area of refuge, b) exit, c) emergency evacuation light showing the direction of movement and d) door in the descending order of priority. Destinations are set for each evacuee and at each time step. Information on destinations and obstacles are controlled separately in each space in the space model. The evacuee except type II occupant can not obtain any information other than that on the space in which he or she is located.

How the evacuee determines the direction and target of movement is shown in Fig. 5. The direction of movement is determined by modeling with vectors the multiple forces acting on the evacuee such as the destinations, surrounding walls, obstacles and other evacuees, and combining vectors. When combining vectors, force of inertia in the direction of movement is given to simulate human movement as realistically as possible. The evacuee is subject to attraction from destinations and repulsion from surrounding walls, obstacles and other evacuees. Repulsive vector is in inverse proportion to the distance between the evacuee and the object.

When setting the destination, the center of the opening is set as the destination point and the number of evacuees allowed to simultaneously pass through the opening is limited according to the effective width of the opening in existing models. In the improved model, setting the destination at any point along the door width is possible.

In the obstacles evasion algorithm, buffer areas for the obstacle, walls and opening equivalent to the radius of the circular area occupied by the evacuee, and virtual points as destinations have been specified. An undirected graph has been developed for the evacuee to find the shortest escape route and set the destination (Fig. 6).

The target of movement is determined for each time step based on the direction of movement identified through vector synthesization, density of people and the walking speed of the evacuee. The walking speed is reduced if the density of people around the evacuee increases. The density of people around the evacuee is calculated in a semicircle with a radius of 3.0 m in the direction of movement. The relationship between the density of people and walking speed is expressed by equation [1].



(a) Determination of buffer area and virtual points

(b) Determination of Edges which connect virtual points

(c) Addition of Edges which connect virtual points and evacuee

(d) Finding the shortest route to the destination

FIGURE 6. Route selection to get around the obstacle in undirected graph

$$V = \min\left(V_0, V_0 / \rho\right) \quad [1]$$

where, V is the walking speed of the evacuee in meters per second. V_0 is the walking speed of the evacuee in meters per second when walking alone. ρ is the density of people around the evacuee per square meter.

For sloped surfaces including flights, walking speed at a given slope gradient has been formulated using equations [2] and [3] by setting the walking speed on a flat surface and that on a reference sloped surface.

$$\begin{aligned} V &= V_0 + (V_1 - V_0)\tau / \theta_1 \\ &= V_0 + (V_1 - V_0)\sin^{-1}\left(\frac{90}{90-\eta}\sin\theta\right) / \theta_1 \end{aligned} \quad [2]$$

$$L = L_0 / \cos\tau \quad [3]$$

where, V is the walking speed in meters per second on a sloped surface. V_0 is the walking speed in meters per second on a flat surface. V_1 is the walking speed on a reference sloped surface in meters per second. L is the distance of movement on a sloped surface in meters. L_0 is the horizontal element of the distance of movement in meters. θ is the angle of the sloped surface to the flat surface in degrees. θ_1 is the angle of the reference sloped surface to the flat surface in degrees. η is the angle of vector in the direction of movement to the direction of slope in degrees. τ is the angle of vector in the direction of movement to the flat surface in degrees.

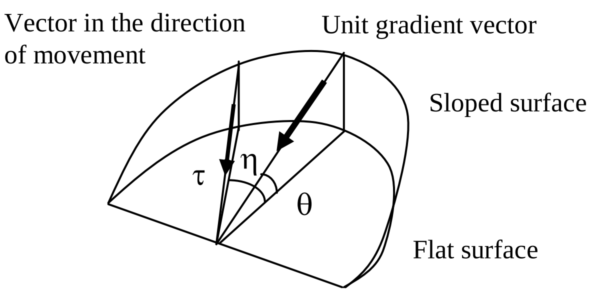


FIGURE 7. Sloped surface and vector in the direction of movement

Smoke Model

The smoke model is used to control the data on the height and temperature of the smoke layer in each room output by a smoke movement simulation model such as BRI2002[6], and to provide information on the condition of smoke in each space in the space model as time passes in simulation. The smoke movement simulation model and evacuation models are independent of each other. Smoke movement in the building is calculated specifying the time for the fire protection system to be operated or the duration in which doors are left open according to a pre-designated scenario. The following effects of smoke flow on evacuation can be considered.

a) Limit state of egress
Limit state of egress expresses state in which the height of smoke layer is less than 1.8 m and the temperature of smoke layer reaches above a reference level in equation [4][7].

$$\int_{t_s}^{t_e} (\Delta T)^2 dt \geq 10,000 \qquad [4]$$

where ΔT is the rise of temperature in the smoke layer. t_s is the starting time of smoke layer exposure. t_e is the limit time of egress. After the room reaches the limit state of egress, the evacuees in the room can no longer continue escape. Evacuees in the other rooms which does not reach limit state of egress can neither use the room in limit state of egress as an escape route nor enter it.

b) Start of evacuation
The evacuee starts evacuation from the room when the height of smoke layer lowers below a certain level (e.g. 90% of the ceiling height).

c) Specification of destination
Emergency evacuation light showing the direction of movement is no longer identifiable when the smoke layer lowers below the height of the evacuation light and the smoke concentration exceeds a reference level (C_s) of 0.3/m.

Evacuation is expected to affect smoke movement. For example, the opening and closing doors during escape may cause the spread of smoke. In this model, however, these effects of evacuation on smoke movement are pre-determined in simulating smoke movement.

CASE STUDIES

Characteristics of Escape in Staircase during the Evacuation of the Entire Building

In this case study, the validity of the model predicting the evacuation in the staircase, which is one of the major improvements in the evacuation model, was examined by comparing calculations with measurements of behavior.

1) Calculation conditions
In the study, the virtual facility shown in Fig. 8 was used. The building had five 4 m high stories. One staircase leading to rooms was installed on each floor. Stairs descended counterclockwise. Evacuees on each floor joined the evacuees in the staircase in the direction of movement of those in the staircase. A 0.9 m wide final emergency exit was installed in the staircase on the first floor for direct escape outside. No effect of fire-induced smoke movement was taken into consideration here.

Two hundred room occupants were randomly located in a 400 m^2 room (density of occupants: 0.5 occupants/m^2) on each floor. An evacuee was assumed to occupy an area with a diameter 0.55 m based on the mean shoulder length of an adult man. Evacuees were assumed to escape under the same conditions. The standard walking speed on a flat surface was set at 1.0 m/sec. Evacuation started at the same time throughout the building. The width of a virtual opening between the landing and flight was set at 1.5 m, same as the width of the flight. In the simulation, calculations were made at intervals of 0.2 s.

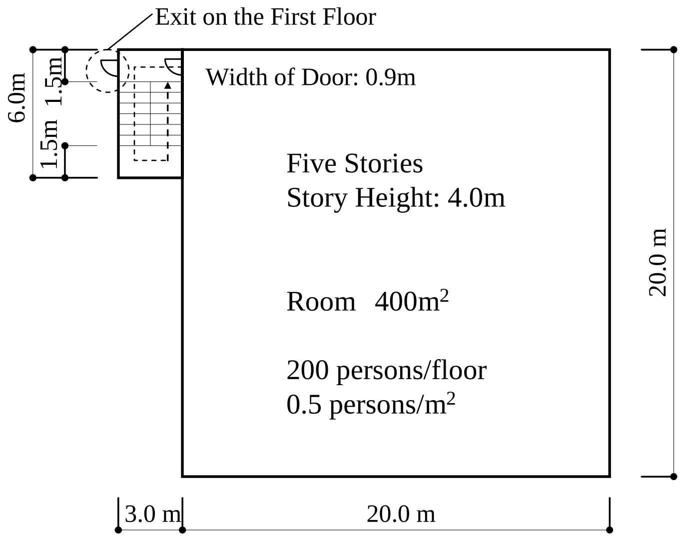


FIGURE 8. Plan of facility for case study

2) Calculation results and discussions

The time to complete evacuation and mean flow rate at final emergency exit on the first floor is shown in Table 1. The number of evacuees who completed evacuation is shown in Fig. 9. Changes in number of evacuees who passed the door of the room on each floor are shown in Fig. 10.

a) flow rate at final emergency exit in the first story

The flow rate was about 1.29 persons/m/sec at a point approximately 300 s after the start of escape and 0.89 person/m/sec thereafter. The mean flow rate was 0.99 person/m/sec. The rate of increase in number of escapees varied before and after about 300 s passed after the start of evacuation. This is because evacuees in the room on the first floor continued escape until 300 s passed since the start of evacuation and were held at the final emergency exit on the first floor, but that subsequently, descending the stairs became a bottleneck and the flow of evacuees in staircases was adversely affected.

TABLE 1. Time to complete evacuation and flow rate at final exit on the first floor

Time to complete evacuation [sec.]	Average flow rate at final emergency exit [persons/m/sec.]
1119	0.99

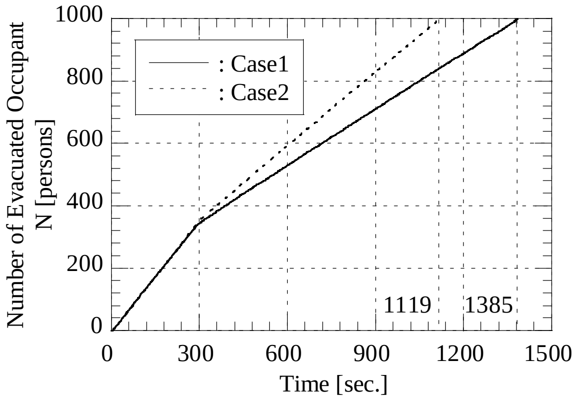


FIGURE 9. Changes in number of evacuated occupants at the final emergency exit

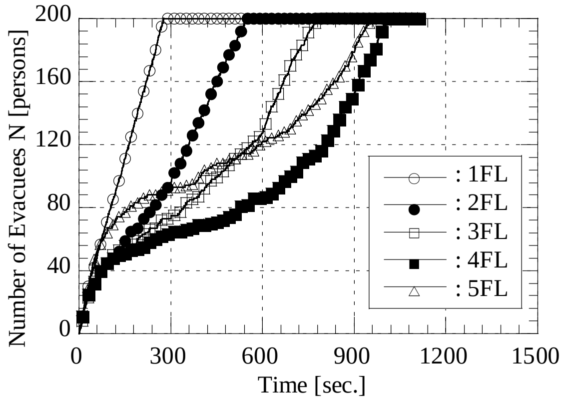


FIGURE 10. Changes in number of evacuees passing through the exit of staircase on each floor

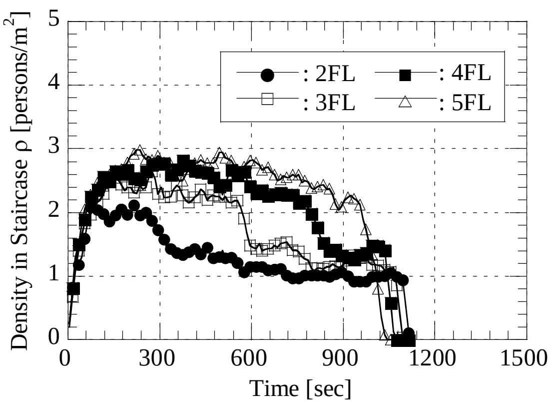


FIGURE 11. Changes in density of evacuees in staircase

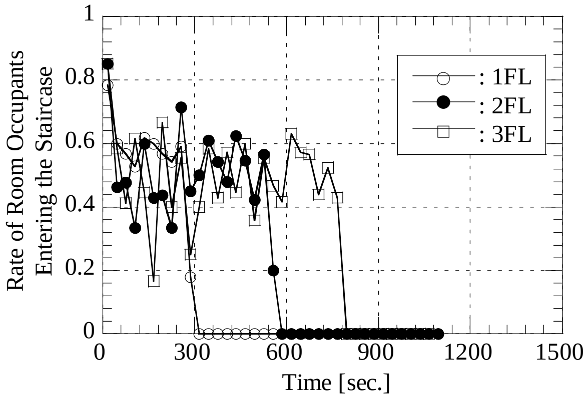


FIGURE 12. Rate of room occupants entering the staircase to evacuees in the staircase

According to the previous study[8], the measured flow rate at the building evacuation in the staircase was about 1.1 persons/m/sec where the staircase was 1.5 m wide. The calculation result was close to the measurement, although slightly lower.

b) Density of people staying in the staircase

Changes in density of people staying in the staircase are shown in Fig. 11. The density is higher on upper floors and tends to decrease with time. The calculated density of people staying in the staircase was approximately one to three per square meter, in the same range of measurements[8]. The calculation was nearly valid.

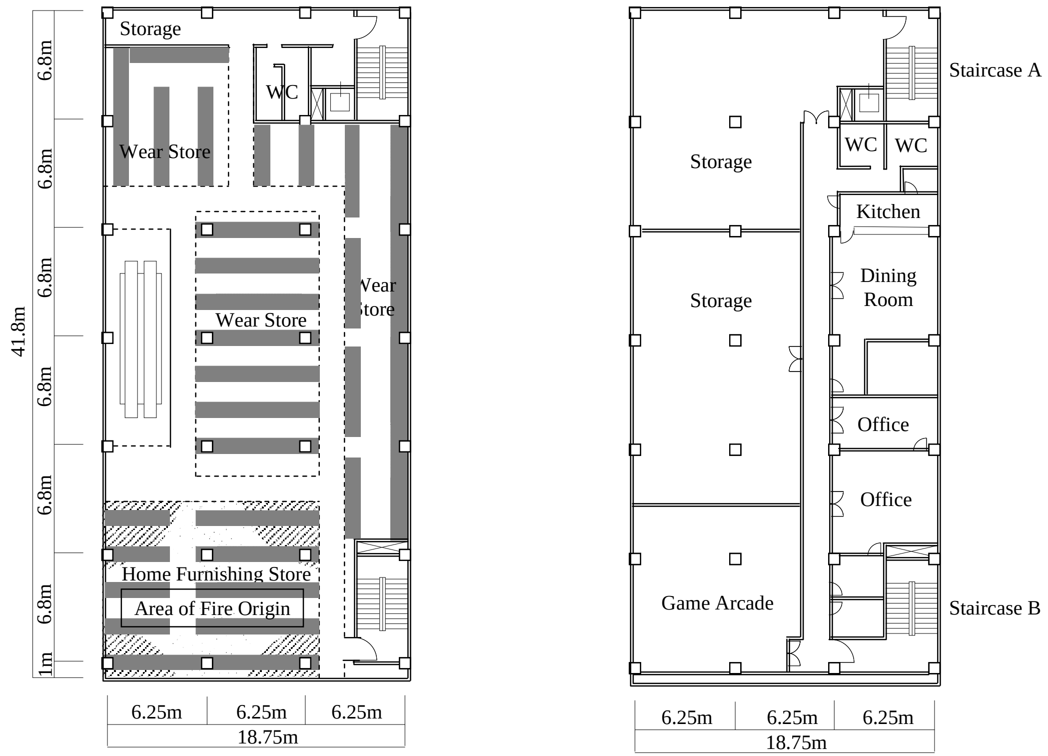
c) Rate of evacuees joining those in the staircase

Changes in rate of evacuees joining those in the staircase on the first through third floors are shown in Fig. 12. Results vary according to the time elapsed. The rate was approximately 0.4 to 0.6. The ratio of evacuees who entered the staircase from the room on the floor to those descending in the staircase was approximately 1:1. In this case study, evacuees were assumed to joint those in the staircase in the direction of movement of those in the staircase. According to the measurements taken under similar joining conditions[9], the rate of joining evacuees was approximately 0.6 in a steady state. The calculations were therefore similar to the measurements.

Then, the prediction of evacuation in the staircase was found to be nearly in agreement with existing measurements and valid.

Reproduction of the Fire of Amagasaki Store of Nagasakiya in 1990

The model was applied to a fire of the Amagasaki store of Nagasakiya of that occurred in Japan in March 1990 to reproduce smoke movement and evacuation.



(a) Forth floor (fire floor)

(b) Fifth floor

FIGURE 13. Plan of the Amagasaki store of Nagasakiya

1) Outline of fire
The Amagasaki store of Nagasakiya is a reinforced concrete retail store with five floors above ground and one basement floor. A typical floor has a floor area of 814 m^2, and the total floor area is 5140 m^2. The selling space occupies the first through fourth floors. The fifth floor accommodates a game arcade, offices, storages and an employee dining room. Fire occurred in the home furnishing store on the fourth floor and spread throughout the floor in about ten minutes. The heat and smoke entered the fifth floor and the third and lower floors via two staircases on the north and the south and elevator shafts. Occupants in the offices and employee dining room on the fifth floor failed to start evacuation early and were forced to take refuge on the floor. High-temperature smoke spread to the fifth floor and killed 15 occupants. Desperate rescue efforts save four through windows.

2) Calculation conditions
Conditions have been set based on some reports on the fire[10, 11] for modeling the space in the building, and for calculating the aggravation of fire and start time of evacuation. Smoke movement in the building has been calculated using BR12002[6].

a) Fire and environmental conditions
The fire broke out in the home furnishing store on the fourth floor. The fire source was modeled as equation [5].

$$Q = \alpha (t - t_0)^2 \qquad [5]$$

where Q is heat release rate of fire source in kW. α is fire growth rate in kW per square second. t_0 is the length of the incubation period after the outbreak of fire in second.

No employee noticed the fire when a fire detector detected it 120 s after it broke out. Then, the fire was regarded as non-flaming burning until 90 s passed after it started and t_0 was expressed by 90 s. Flame reached the ceiling 180 s after the outbreak of fire, or 90 s after flaming. Fire growth rate was set at 0.083 kW/sec^2 and Q_{max} at 25 MW (640 s) so that the height of intermittent flame could reach the height of ceiling (2.7 m) in 180 s after the outbreak of fire. Outside temperature is set at 12°C. Outdoor wind velocity is 9 m/sec from west-southwest direction.

b) Evacuation conditions

The numbers of evacuees and when they started evacuation are listed in Table 2. The walking speed of evacuees on the flat floor was set at 0.5 m per second in selling space or 0.8 m per second in other area. The standard walking speed on the escalator was set at 0.8 m per second for gradient of 20 degrees.

3) Calculation results and discussions

The numbers of evacuees who used the escalator for evacuation on the second through fourth floors are shown in Fig. 14. Most of the fourth-floor occupants were led by sales clerks to evacuate via escalator section. Calculation results show that all completed escape from the fourth floor 296 s after the outbreak of fire while the escalator section on the fourth floor were exposed to smoke 330 s after the outbreak of fire and later.

TABLE 2. Numbers of evacuees and time to start evacuation of the Amagasaki store of Nagasakiya

Floor	Occupancies	Time to start evacuation after the start of fire	Number of Evacuees at the start of fire
5th floor	Game arcade	8 minutes	5
	Office		2
	Employee dining room		14
4th floor	Wear store Home furnishing store	4 minutes	20
3rd floor	Wear store	5 minutes	30
2nd floor	Wear store	6 minutes	30
1st floor	Daily miscellaneous goods store Cosmetics store	6 minutes	30
		Total	131

Fig. 15 shows the example output of evacuation simulation on the fifth floor. Occupants on the fifth floor were late in starting evacuation, approximately eight minutes after fire broke out. At the point, the passageway on the fifth floor was polluted by smoke transported via the staircase B and reached a limit state of egress (450 s after the outbreak of fire). The fifth-floor occupants could therefore not go out of the room into the passageway and were forced to take refuge in the room.

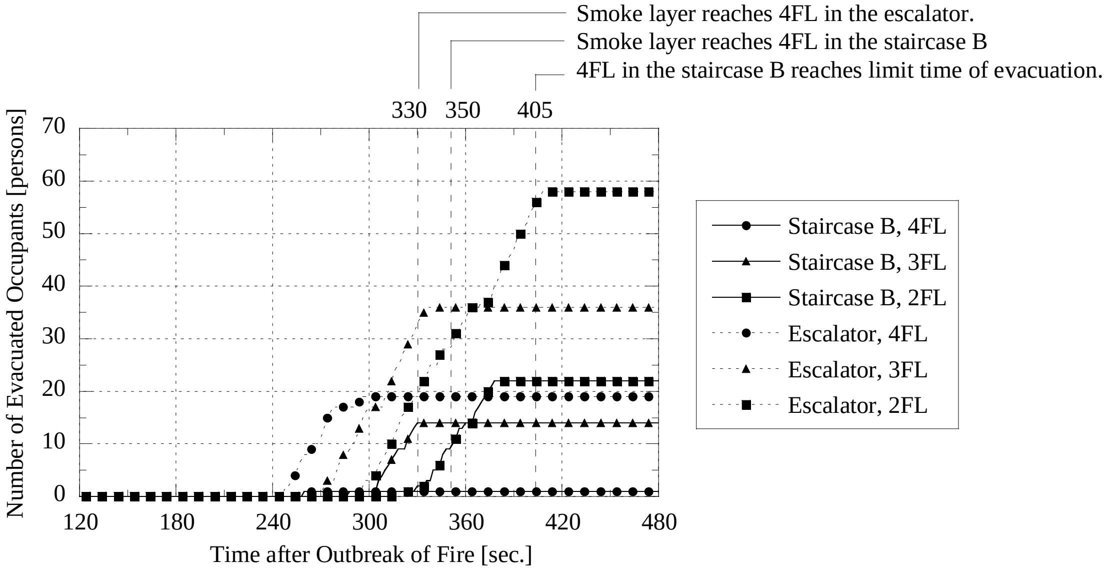
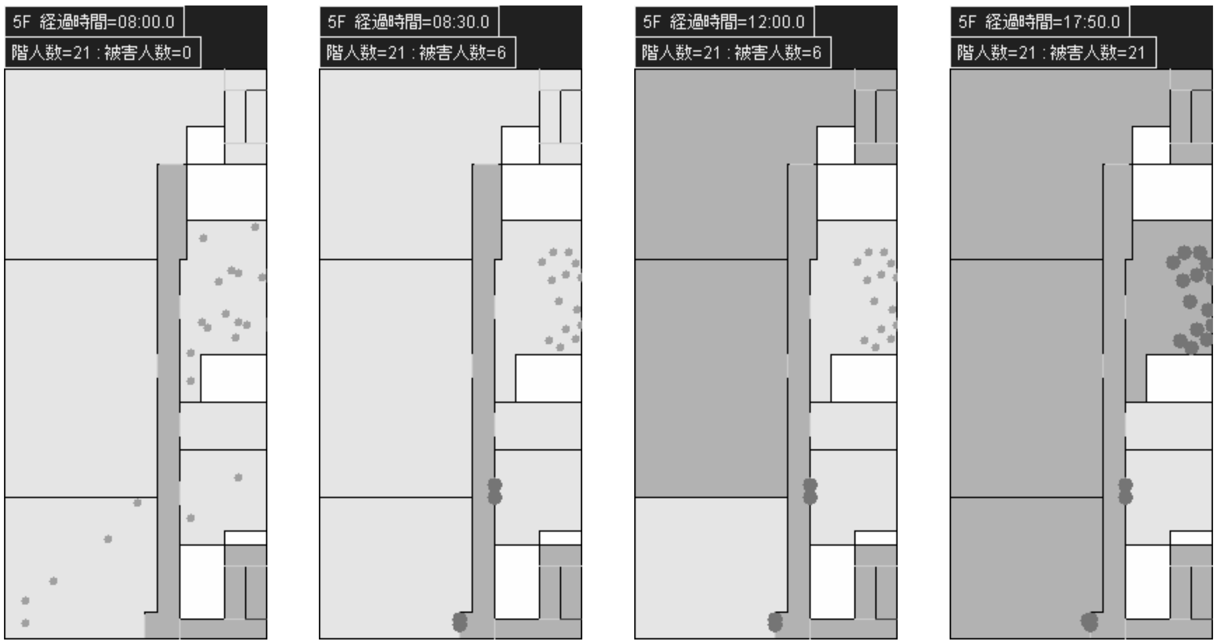


FIGURE 14. Numbers of evacuees on the second through fourth floors



(a) 8’00” (b) 8’30” (c) 12’00” (d) 17’50”

FIGURE 15. Example output of evacuation simulation on the 5th Floor

The condition at the site was well represented by calculations. The staircase A reached the limit state of egress at 595 s after the fire broke out. The calculated condition matches the report of a guard that the fire rapidly aggravated on the fourth floor in approximately ten minutes of the outbreak of fire and that black smoke started bursting into the staircase A.

CONCLUSIONS

This study presented an evacuation simulation modeling method, gave case studies of evacuation of an entire building and examined the validity of the calculation model. The study revealed that the results of evacuation prediction when an entire building was evacuated were nearly in agreement with exiting measurements and were valid. Also, case study for the reproduction of the fire accident in the retail store revealed that the evacuation behavior under the smoke movement can be represented by the model. In the future, further studies will be made under various conditions to verify the validity of and improve the model.

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