Research Paper

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Earthquake evacuation simulation of multi-story buildings during earthquakes

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Abstract

Through combining a network-based pedestrian dynamics simulation model, simplified probabilistic structural damage assessment, and structural random vibration analysis, a fully random evacuation model is proposed for simulating and analyzing earthquake evacuation processes of multi-story buildings during earthquakes. The model simplifies the simulation of three-dimensional pedestrian dynamics, couples the emergency evacuation processes and damage processes of structures, and takes into account the randomness of pedestrian dynamics, structural damage, and earthquake excitation. The model can be used for the fast pre-evaluation or evaluation of the earthquake evacuation capabilities of multi-story buildings. The simulation and analysis of the earthquake evacuation process of a three-story office building, in which a total of 60 persons work in the first and second stories, illustrates the effectiveness and implementation of the proposed model.

Keywords

Earthquake evacuation, multi-story buildings, cellular automata, network graph, seismic damage

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Introduction

The earthquake evacuation models of multi-story buildings have attracted more and more research interest in the past decade (Castro et al., 2019; Nishino et al., 2013; Yun and Hamada, 2015). The models can provide the structural and architectural designers as well as technicians of urban disaster prevention and mitigation with information about the motion routes, total evacuation time (TET), and casualties of people in the buildings during and/or after earthquakes. Based on the information, the optimal earthquake escape ways during earthquakes for new buildings can be designed or the most likely places of the casualties after earthquakes for the existing buildings can be predicted. Since there exist a lot of randomness related to pedestrian dynamics, structural damage and earthquake, the motion routes, TET, and casualties are all uncertain.

One key issue to be solved by the earthquake evacuation models is the pedestrian dynamics simulation. A large number of macroscopic and microscopic pedestrian dynamics simulation models have been developed in the past several decades. Among them, the most popular models are the social force model (Helbing et al., 2000; Helbing and Molnar, 1995), cellular automata model (Biham et al., 1992; Nagel and Schreckenberg, 1992; Schreckenberg et al., 1995), lattice-gas model (Helbing et al., 2003; Nagai et al., 2004), and agent-based model (Bonabeau, 2002). The social force model is a continuous model in which the pedestrians are treated as particles subject to long-ranged forces induced by the social behavior of the individuals. In the social force model, the change of velocity in time t can be determined by the socio-psychological and physical forces through solving an acceleration equation. Recent developments of the social force model are to introduce new forces or factors into the model to take into account the group and age-driven behaviors (Gorrini et al., 2016), head and group phenomena (Farina et al., 2017), parameter identification based on real video data (Liu et al., 2018), and so on.

In contrast to the social force model, the cellular automata model is a discrete model in which the evacuation area is discretized into a number of cells and each cell can be empty or occupied by a particle or an obstacle object. It is extremely important for the cellular automata model to take into account the interactions between environments and pedestrians as well as pedestrians and pedestrians. Numerous cellular automata models have been proposed in the past two decades to consider the interactions (Burstedde et al., 2001; Kirchner et al., 2003; Muramatsu et al., 2000; Song et al., 2006; Yu and Song, 2007). Among them, the floor field cellular automata model translates the long-ranged interaction to local interaction by introducing the concept of the dynamical field (Burstedde et al., 2001). The more in-depth researches on the floor field cellular automata model have been carried out to investigate the impact of sensitivity parameters (Kirchner and Schadschneider, 2002), improve the efficiency of simulation (Nishinari et al. 2005), extend the range of application (Fu et al. 2017; Schadschneider, 2003), and consider human behavior (Ha et al., 2012). The lattice-gas model is also a discrete model and a special type of the cellular automata model. This model is particularly suitable for modeling counter flow in different situations (Huo et al., 2013; Kuang et al., 2008).

The agent-based model is a microscopic model in which a system is modeled as a collection of autonomous decision-making entities denoted as agents. At each time instant, each agent individually assesses its surrounding environment and makes decisions on the basis of a set of rules (Bonabeau, 2002; Poulos et al., 2018). Through combining the cellular automata and multiple agents, several agent-based evacuation models have been developed for building evacuation simulation (Cimellaro et al., 2017; Shi et al., 2009). The remarkable advantage of the agent-based model is that it can take full account of human behavior and social factors in pedestrian dynamics (Aguirre et al., 2011); it, therefore, has been used to simulate and analyze the fire evacuation (Aguirre et al., 2011), earthquake evacuation (Cimellaro et al., 2017; Liu et al., 2016; Poulos et al., 2017, 2018), and tsunami evacuation (Mas et al., 2013). A disadvantage of the agent-based model is that it usually requires high computational costs to simulate the evacuation processes of multi-story buildings.

Another key issue to be solved by the earthquake evacuation models is to couple the emergency evacuation process and structural damage process. Xiao et al. simulated the household evacuation considering the damage due to an earthquake. However, this study only estimated the acquired safety escape time by structural damage analysis and did not couple the structural damage processes and evacuation process (Xiao et al., 2016). Li et al. (2015, 2018) developed a method for casualty prediction in a single-story high school building during an earthquake, in which they assumed that if the relative displacement between the positions in upper- and lower-floor slabs is smaller than a critical value and those positions in the lower slab are occupied by occupants, then casualties occur. In fact, they coupled the slab collapse processes and evacuation processes but did not consider the influence of the non-structural and structural damage processes on evacuation processes in building evacuation simulation. Liu et al. (2016) and Cimellaro et al. (2017) assumed that the evacuation starts at the end of the earthquake and did not consider the agents' behavior during the ground shaking in the evacuation simulation; therefore, they focused on the simulation of building evacuation after an earthquake. Poulos et al. (2017) proposed a numerical algorithm to combine the probabilistic seismic hazard analysis, inelastic structural response analysis, damage assessment, and response of evacuation agents. This study considered the evacuation process at the same time of the earthquake through coupling non-structural damage field and time when damages are reached with agents' evacuation.

The third key issue to be solved by the earthquake evacuation models is to reduce the computational complexity of three-dimensional evacuation simulation. For a multi-story building in which different floors are linked by staircases, pedestrians will move in a three-dimensional space. Hu et al. (2015) used a three-dimensional cellular automata model with von Neumann neighborhood to simulate the pedestrian dynamics in multi-story buildings. Li et al. (2017) proposed a stair-unit model to describe the structural topologies and the spatial relationships of a part of a twisting stairwell, whereby the social force model can be used to effectively simulate the pedestrian dynamics in multi-story stairwells and buildings. Essentially, the stair-unit model simplifies the three-dimensional pedestrian dynamics simulation to a two-dimensional problem.

The main subjective of this study is to propose an effective earthquake evacuation model for multi-story buildings through solving the existing three problems, that is, the complexity of three-dimensional pedestrian dynamics simulation, coupling of the structural damage processes and evacuation processes, and randomness of the pedestrian dynamics, structural damage, and earthquake excitation. To propose the evacuation model, a network modeling technique is developed first to construct the whole network for the discretized evacuation area of multi-story buildings such that the pedestrian dynamics can be effectively simulated, then a simplified method is developed for analyzing the random nonlinear responses and damage of structures due to earthquakes, and finally, a new method is proposed to couple the evacuation processes and structural damage processes through redefining the states of the network vertices and particles in the pedestrian dynamics simulation. The model can fast pre-evaluation or evaluate the earthquake evacuation

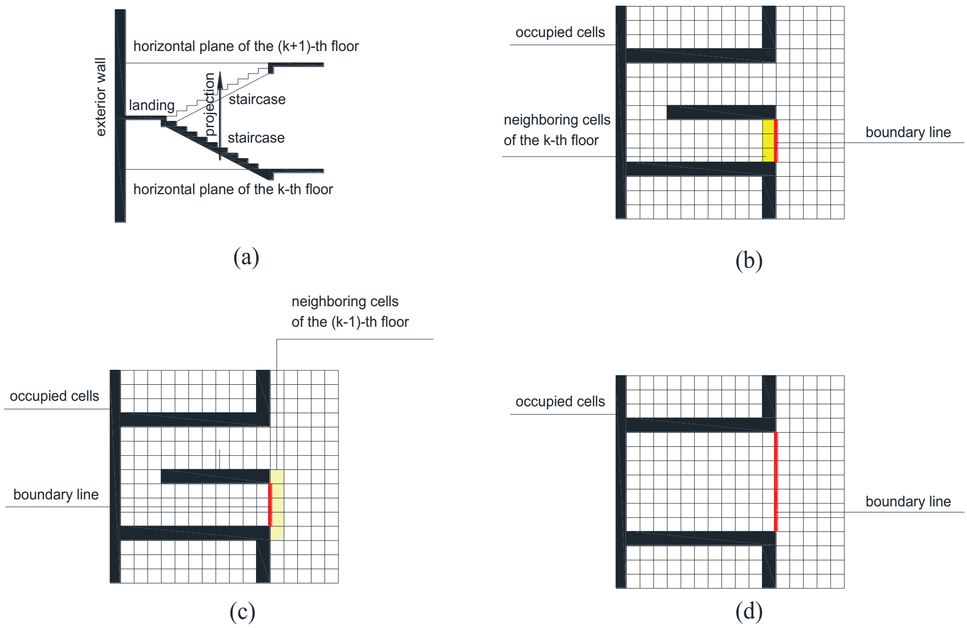


Figure 1. Illustration of discretizing the evacuation area and constructing the grids of cells: (a) stairwell, (b) plane of the (k + 1)th floor, (c) plane of the kth floor, and (d) plane of the first floor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

capabilities of multi-story buildings. An illustrative example is presented to demonstrate the effectiveness and implementation of the proposed model.

Pedestrian dynamics simulation of multi-story buildings

Grids of cells and whole network

In this study, the concept of the cellular automata model is used to establish a network-based evacuation simulation model for multi-story buildings. The steps for constructing the network used in the evacuation simulation are as follows: First, project the upper surfaces of the staircases and platform between every two adjacent floor slabs vertically onto the horizontal plane of the upper floor slab. Second, discretize the $k = 1, \ldots, K$ horizontal plane which consists of the evacuation area of the kth story and the vertical projection of the staircases and platform just below it and construct the corresponding grids of cells. Here, K is the number of stories. Third, choose the type of neighborhood of cells (Von Neumann neighborhood or Moore neighborhood) and determine the neighboring cells that allow the particle in the central cell to move into. Finally, construct an undirected network through setting the centers of cells to be vertices and the lines between the centers of the neighboring cells which are allowed to move into for each other to be edges. The lengths of the edges of the network are set to be 1 or $\sqrt{2}$. The modeling technique of the whole network is illustrated in Figures 1 and 2, in which the Moore neighborhood is used. Note that, in Figure 1b and c, the boundary lines indicate that the cells which are on both sides of them are not allowed to move into for each other, while the cells in yellow indicate that they are neighboring cells between the kth and (k + 1)th floors and are allowed to move into for each other. In addition, since the pedestrians on the first floor are not

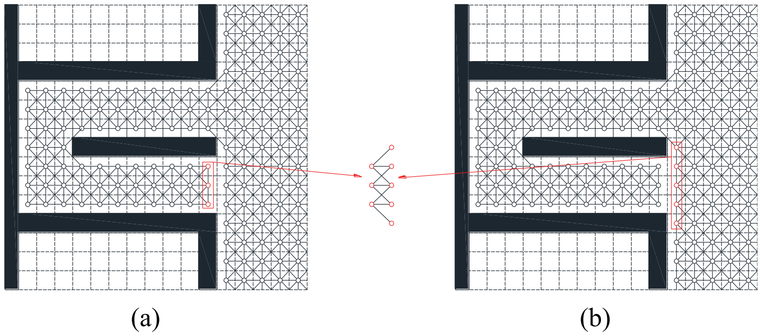


Figure 2. The interconnected networks on the kth and (k + 1)th floors: (a) plane of the (k + 1)th floor and (b) plane of the kth floor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

expected to move into the stairwell, there is a boundary line on the border of the stairwell, as shown in Figure 1d.

Network-based pedestrian dynamics simulation

In order to propose the network-based evacuation simulation model, it is assumed that each vertex of the generated network can either be empty or occupied by exactly one particle (pedestrian) and a single particle moves with a velocity of one vertex per time step. The move of a particle is determined by a vector of transition probabilities $P_i = [p_{i,0}, p_{i,1}, \ldots, p_{i,k_i}]$, in which $p_{i,0}$ is the probability that the particle i keeps its position and $p_{i,j}, j = 1, \ldots, k_i$ are the probabilities that the particle i moves to its adjacent vertices, where k_i denotes the number of the adjacent vertices of the considered vertex i. The value of $p_{i,0}$ depends on the states of the adjacent vertices of the vertex i, that is, $p_{i,0} = 1$ if the adjacent vertices are all occupied by the obstacles and $p_{i,0} = 0$ if any adjacent vertex of the vertex i is empty. The transition probabilities $p_{i,j}, j = 1, \ldots, k_i$ are calculated according to the floor field cellular automata model (Burstedde et al., 2001):

$$p_{i,j} = N\exp(\beta J_s \Delta_s(i,j))\exp(\beta J_d \Delta_d(i,j))\left(1 - n_j\right)d_{i,j}, \quad j = 1, \ldots, k_i \tag{1}$$

in which

$$\Delta_s(i,j) = \tau_s(j) - \tau_s(i), \quad j = 1, \ldots, k_i \tag{2}$$

$$\Delta_d(i,j) = \tau_d(j) - \tau_d(i), \quad j = 1, \ldots, k_i \tag{3}$$

where $\tau_s(j),\ j = 1, \ldots, k_i$ and $\tau_s(i)$ are, respectively, the static potential of the vertices j and i; $\tau_d(j),\ j = 1, \ldots, k_i$ and $\tau_d(i)$ are, respectively, the dynamic potential of the vertices j and i; the parameter $n_j = 1$ if the vertex j is occupied by an obstacle; and $n_j = 0$ if the vertex j is empty, N is a normalization factor to ensure $\sum_{j=0}^{k_i} p_{i,j} = 1$, $d_{i,j}$ is a correction factor taking into account the direction the particle in the vertex i has been coming from, the variables J_s and J_d control, respectively, the coupling strength between the particles and the static and the dynamic potential, and β plays the role of an inverse temperature. Note that the parameter n_j will be modified by the damage processes of structures, as described later.

The static potential $\tau_s(k)$ of each vertex k of the whole network is

$$\tau_s(k) = \min_{1 \leqslant l \leqslant L}\left\{\max_{1 \leqslant i \leqslant K} D_{i \to l} - D_{k \to l}\right\} \tag{4}$$

in which L is the number of the terminal vertices of the whole network, K is the total number of the vertex of the whole network, $D_{i \to l}$ denotes the shortest distance from a vertex $i = 1, \ldots, K$ to a terminal vertex l, and $D_{k \to l}$ denotes the shortest distance from the vertex k to a terminal vertex l, where l runs over all vertices of the whole network.

The dynamic potential $\tau_d(j), \quad j = 1, \ldots, k_i$ and $\tau_d(i)$ are calculated as follows. At the beginning of a simulation each $\tau_d(k), \quad k = 1, \ldots, K$ is fixed to be a specific value. Whenever a particle moves from a vertex k into one of its neighboring vertices, $\tau_d(k)$ is increased by one. After all motions of the particles during one time step have been performed, the dynamic potential is decreased by one with probability α, if it has been created during the previous update step or earlier.

The correction factor $d_{i,j}$ is calculated as follows: If the particle at the cell corresponding to the vertex i has been sitting at the cell corresponding to the vertex j at time $t - 1$, setting

$$d_{i,j} = \exp(-\beta J_d), \quad j = 1, \ldots, k_i \tag{5}$$

If during the time step from $t - 1 \to t$, the particle has moved into the direction of the vector pointing from the cell corresponding to the vertex i to the cell corresponding to the vertex j, setting

$$d_{i,j} = \exp(\beta J_0), \quad j = 1, \ldots, k_i \tag{6}$$

where J_0 is a parameter which can be used to tune the inertia of the particle. In all other cases

$$d_{i,j} = 1, \quad j = 1, \ldots, k_i \tag{7}$$

Note that the problem of conflicts is solved according to the relative transition probabilities, as described by Burstedde et al. (2001).

Coupling of evacuation processes and damage processes

Probabilistic assessment of damage of structures

According to the principle of performance-based seismic design for structural engineering, the probabilities of occurrence of non-structural damage, structural damage, and structural collapse in the *i*th story of a multi-story building are identical to the probabilities that the corresponding inter-story drift ratio responses exceed in magnitude the specified

Table 1. Thresholds of inter-story drift ratio of a reinforced concrete frame structure

Type	Non-structural damage	Structural damage	Structural collapse
Threshold	1/400	1/200	1/50

Table 2. Percentages of damaged non-structural elements of a reinforced concrete frame structure

Type	First story (%)	Second story (%)	Third story (%)
Suspended ceiling	47.6	42.6	78.8
Office work stations	80.0	48.1	44.4
Objects on shelves	88.3	86.8	76.3
Desktop electronics	93.3	90.0	91.7
Objects on racks	93.3	100.0	80.0

Table 3. Area percentages of damaged structural elements of a reinforced concrete frame structure

Story	Structural elements (%)
1	2.6
2	1.4
3	2.9

thresholds in the reference duration. The thresholds should be determined from the correlation analysis of the structural element deformations and inter-story drift ratios. For the reinforced concrete frame structures, the thresholds are defined by some performance-based seismic design codes, and for a three-story reinforced concrete frame structure, the threshold levels are listed in Table 1 (CECS 160-2004, 2004; Structural Engineers Association of California, 1995). For each earthquake excitation sample, the percentages of the damaged non-structural and structural elements should be determined from the fragility analysis of the considered structure (Cimellaro et al., 2017). Since the number of earthquake excitation samples required by the evacuation simulation is usually large, the computational efforts may be infeasible if the percentages are determined using the above method. To reduce the computational efforts, it is assumed in this study that, after the occurrence times of damage, the percentages of the damaged non-structural elements of a reinforced concrete frame structure are identical to the mean values of the total percentages of the damaged non-structural elements calculated from the 16 earthquake input time histories (Cimellaro et al., 2017). The obtained values are listed in Table 2 for a three-story reinforced concrete frame structure. Similarly, in order to determine the area percentages of the damaged structural elements of a reinforced concrete frame structure when its structural damages happen, it is assumed in this study that the pedestrian's injury caused by the damaged structural elements is serious injury and, moreover, the area percentage of the damaged structural elements is identical to the percentage of the seriously injured people for each story. According to the analysis results of Cimellaro et al. (2017), the area percentages of the damaged structural elements of a three-story reinforced concrete structure are determined and listed in Table 3. As for structural collapse, it is assumed in this study that if there occurs structural collapse for a certain story, then 100% of the pedestrians on the corresponding floor will be seriously injured or killed and all the network vertices corresponding to the floor will be occupied by obstacles.

Occurrence times of damage of structures

The occurrence times of seismic damage of structures are uncertain due to the randomness of earthquakes. Assuming that the structural failures are brittle, the occurrence times can be defined as the first passage times of the inter-story drift ratios over the thresholds corresponding to non-structural damage, structural damage, and structural collapse. The sample first passage times t_i^{NS}, t_i^S, and t_i^C of non-structural damage, structural damage, and structural collapse can be expressed as, respectively:

$$t_i^{NS} = \min\left[|\delta_i(t)| \geqslant \hat{\delta}_i^{NS}\right], \quad i = 1, \ldots, K \tag{8}$$

$$t_i^{S} = \min\left[|\delta_i(t)| \geqslant \hat{\delta}_i^{S}\right], \quad i = 1, \ldots, K \tag{9}$$

$$t_i^{C} = \min\left[|\delta_i(t)| \geqslant \hat{\delta}_i^{C}\right], \quad i = 1, \ldots, K \tag{10}$$

where $\delta_i(t)$ is a sample of the inter-story drift ratios of the ith story, $\hat{\delta}_i^{NS}$, $\hat{\delta}_i^{S}$, and $\hat{\delta}_i^{C}$, $i = 1, 2, \ldots, K$, are, respectively, the allowed inter-story drift ratios corresponding to non-structural damage, structural damage, and structural collapse of the ith story. The sample responses $\delta_i(t), \quad i = 1, \ldots, K$ can be obtained by the Monte Carlo simulation methods (He, 2009; He and Gong, 2016).

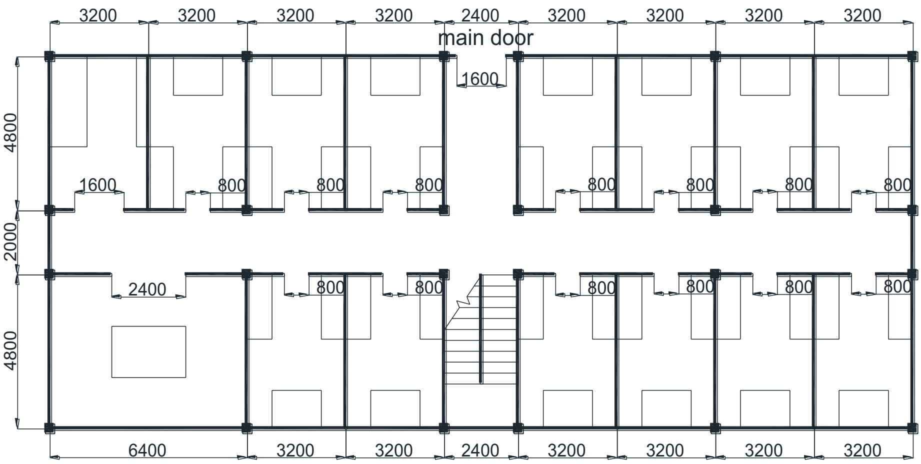
Coupling of evacuation processes and damage processes

As mentioned above, both the evacuation process and damage of structures are random or uncertain. In order to couple them, a simulation method is proposed and described as follows: First, construct the initial grids of cells and whole network for a multi-story building without considering non-structural damage, structural damage, and structural collapse. Second, calculate N inter-story drift ratio responses of the structure using the Monte Carlo method. Third, for each inter-story drift ratio response sample, calculate the occurrence times of non-structural damage, structural damage, and structural collapse for each story. Fourth, randomly generate N distributions on the evacuation areas of the damaged non-structural elements and damaged structural elements and determine the occupied vertices of the whole network. Fifth, for each inter-story drift ratio response sample, simulate the pedestrian dynamics in the building starting from the initial whole network, which are modified according to the occurrence times of non-structural damage, structural damage, and structural collapse for each story. Finally, statistically analyze the earthquake evacuation process from the N simulation results.

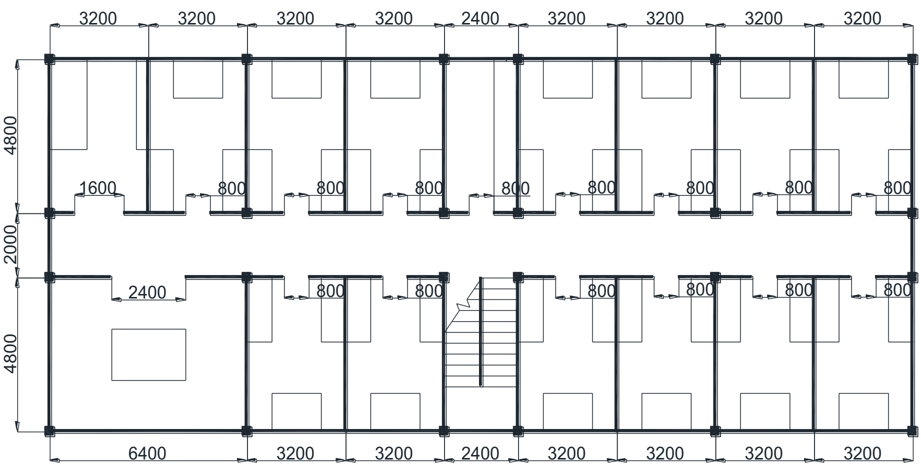
Note that the random distributions on the evacuation areas of the damaged non-structural elements and damaged structural elements are generated using the percentages listed in Tables 2 and 3, respectively. For the situation of structural collapse, the collapsed structural elements will distribute the whole evacuation areas of the corresponding story. In addition, it is assumed that the particles (pedestrians) will be seriously injured or killed if the structural elements fall down on the sites occupied by them.

Illustrative example

This example is presented to demonstrate the effectiveness and use of the proposed evacuation simulation model in simulating the emergency evacuation processes of multi-story buildings during earthquakes. For the analysis, MATHEMATICA 11 was used on a computer with an Intel I7 CPU (2.5 GHz each) and 8 GB of RAM.



(a)



(b)

Figure 3. Plan layout of the official building (unit: mm): (a) the first floor and (b) the second floor.

Brief description of the problem

The building considered in this example is a three-story office building; however, at present, only the first and second stories are in use. The plane layouts of the first and second stories are shown in Figure 3, in which the rectangles with the thin solid lines denote the desks, shelves, racks, toilets or urinals, and so on. There are no suspending ceiling and office work stations in the building. Under normal circumstances, there are 60 staff working in the building, that is, 33 staff in the first story and 27 staff in the second story. The structural type of the building is reinforced concrete frame with the strength grade of concrete C30. The layout of column system is shown in Figure 3 and a common framework is shown in Figure 4a.

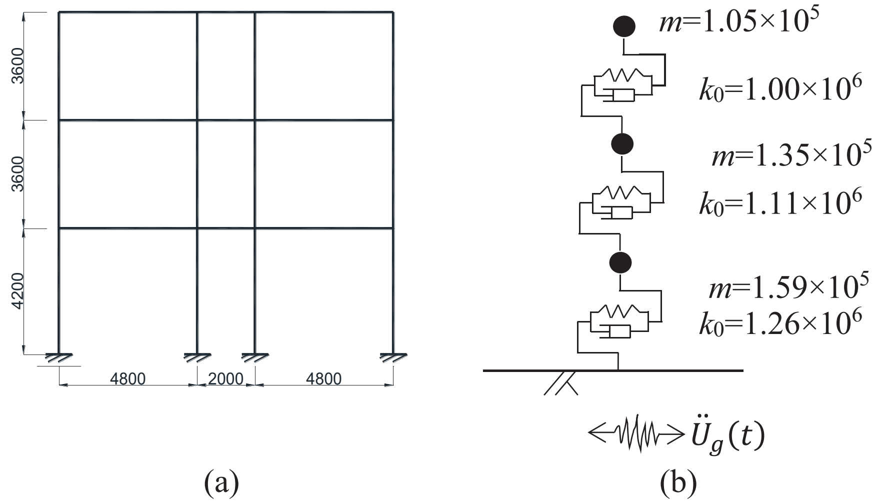


Figure 4. Frame structure and its simplified dynamic model: (a) frame structure model (unit: mm) and (b) shear-building model (unit: 105 kg; 106 kN/m).

Occurrence times of damage

To save the computational cost, the frame structure is modeled as a shear structure. The three-story shear-building model of the frame structure is shown in Figure 4b, from which the natural periods of modes 1 and 2 are calculated as 0.453 and 0.177 s. Rayleigh damping with 5% damping ratio in modes 1 and 2 is assumed in the response sample analysis of the model. The hysteretic restoring force of each story is defined as follows:

$$f_S = k_0[\alpha\Delta X + (1-\alpha)Z] \tag{11}$$

where k_0 is the initial story stiffness; $\alpha = 0.1$ represents a nonlinearity parameter; ΔX and Z, respectively, represent the elastic and hysteretic components of the inter-story displacement; and Z follows the well-known Bouc–Wen hysteresis law:

$$\dot{Z} = -\gamma|\Delta\dot{X}|Z|Z|^{n-1} - \beta\Delta\dot{X}|Z|^n + A\Delta\dot{X} \tag{12}$$

in which parameter values $n = 2$, $A = 1$, and $\gamma = \beta = A/(2x_y^n)$, where $x_y = 0.01\,\text{m}$ is the yield displacement.

The earthquake excitation is modeled as $\ddot{U}_g(t) = m(t)\ddot{U}(t)$, where $m(t)0.0930t^3\exp(-0.5t)$ is the modulating function (Fujimura and Der Kiureghian, 2007), in which $\ddot{U}(t)$ is a stationary Gaussian process with zero mean and the well-known Kanai-Tajimi power spectrum density:

$$S(\omega) = S_0\frac{\omega_f^4 + 4\omega_f^2\zeta_f^2\omega^2}{\left(\omega^2 - \omega_f^2\right)^2 + 4\omega_f^2\zeta_f^2\omega^2} \tag{13}$$

in which $S_0 = 0.03\,\text{m}^2/\text{s}^3$, $\omega_f = 15.7\,\text{rad/s}$, and $\zeta_f = 0.6$.

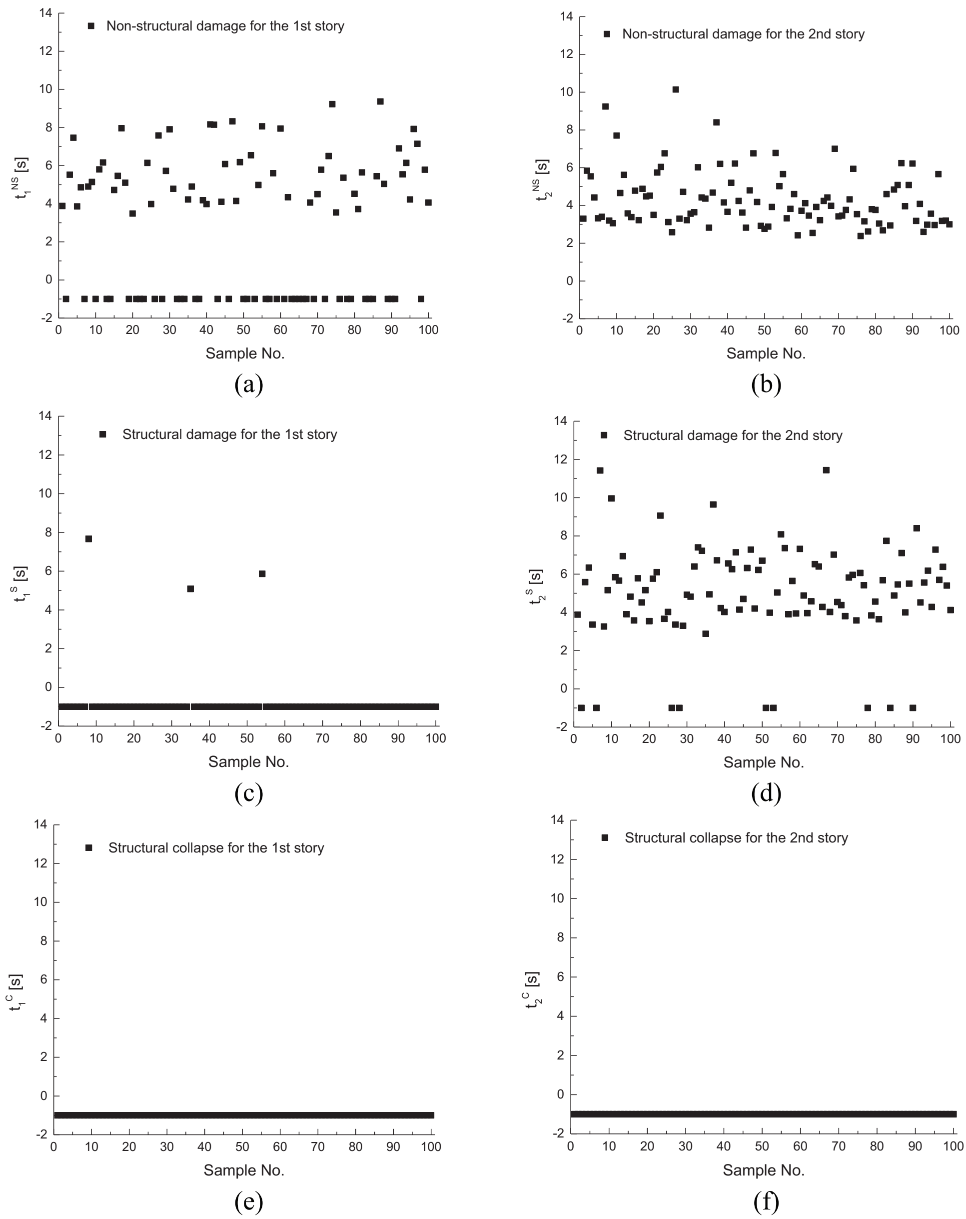


Figure 5. First occurrence times of structural damage: occurrence times of (a) non-structural damage for the first story, (b) non-structural damage for the second story, (c) structural damage for the first story, (d) structural damage for the second story, (e) structural collapse for the first story, and (f) structural collapse for the second story.

A total of 100 inter-story drift ratio response samples are calculated, from which 100 occurrence time samples of non-structural damage, structural damage, and structural collapse of the considered structure are estimated and plotted in Figure 5. Note that, in the calculation of the response samples, the structural parameters are considered as deterministic since the uncertainty of the structural responses are mainly caused by the randomness

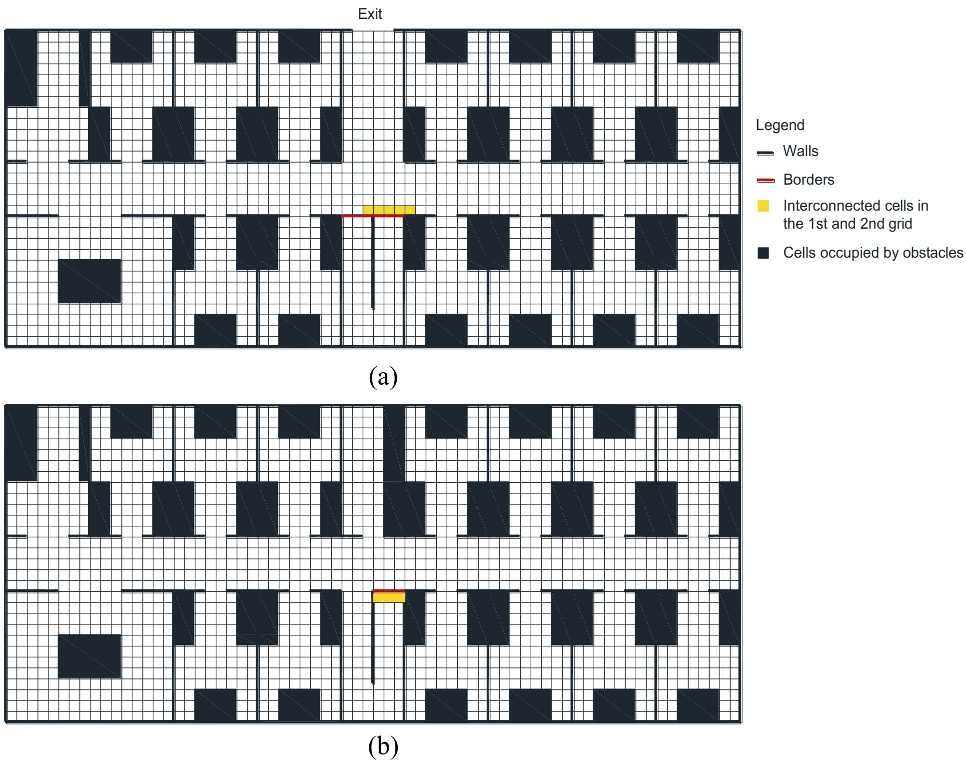


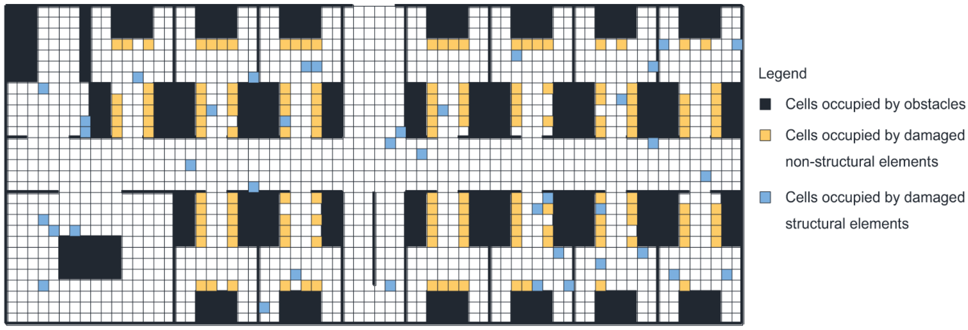
Figure 6. Initial grids of cells for the (a) first floor and (b) second floor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the earthquake excitation. In addition, the first passage times that are not calculated from the sample data are expressed by the number -1 in the figure. Figure 5 shows that, in the reference duration, the occurrence numbers of non-structural damage and structural damage of the second story are greater than those of the first story, and there are no structural collapses for this building. More importantly, it can be seen in Figure 5 that the randomness of earthquake causes the significant uncertainty of the occurrence times of non-structural damage and structural damage, which leads to the greater variability of the evacuation process analyzed later.

Initial conditions and damage element distributions

Setting the size of each cell to be $40\times40\,\text{cm}^2$, the initial grids of cells for the first and second floors are plotted in Figure 6. From the grids of cells, the initial whole network for the evacuation simulating can be constructed.

For an arbitrarily selected inter-story drift ratio response sample, for example, the one corresponding to the eighth occurrence time sample of damage shown in Figure 5, the occurrence times of non-structural damage, structural damage, and structural collapse are, respectively, 4.9 s, 7.66 s, and infinity for the first story and 3.2 s, 3.26 s, and infinity for the second story. At these moments, the initial grids of cells, whole network, as well as the states (living or dead) of particles (pedestrians) must be modified according to a randomly



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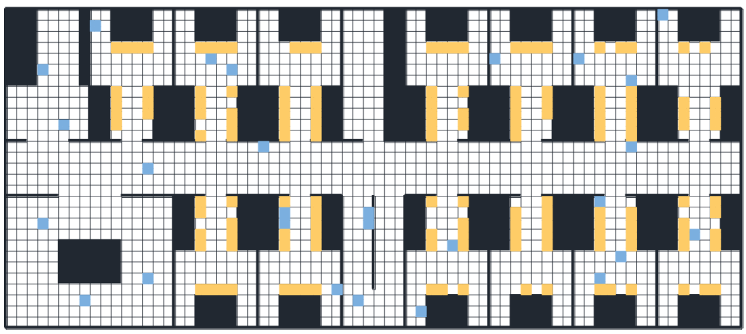

(b)

Figure 7. A realization of the random distributions of the damaged elements on the floors: (a) the first floor and (b) the second floor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

generated distribution on the floors of the damaged non-structural elements, damaged structural elements, and collapsed structural elements. A randomly generated distribution of the damaged elements is plotted in Figure 7. To generate the distribution of the damaged non-structural elements, we first randomly select the damaged non-structural elements according to the percentage of them, and then randomly generate their scattered area on the floors. To generate the distribution of the damaged structural elements, we assume that the damaged floor slabs, beams, and columns of the building will uniformly scatter on the floor just below them. Therefore, the distribution of the damaged structural elements is generated by randomly selecting the cells on the corresponding floors according to the area percentage of the damaged structural elements. In addition, if a selected cell related to the damaged structural elements is the one that has been occupied by the obstacles or scattered non-structural elements, this indicates that the corresponding damaged structural elements fall on the obstacle or the scattered non-structural elements; therefore, the states of the cell and corresponding vertex of the whole network will not be influenced by the damaged structural elements.

Simulation and analysis of the evacuation process

It is assumed that the 60 staff begin to evacuate from the building 10 s early than arrival of the earthquake wave due to the earthquake early warning system. According to the common state on weekdays, the distribution of the 60 staff at the moment when they begin

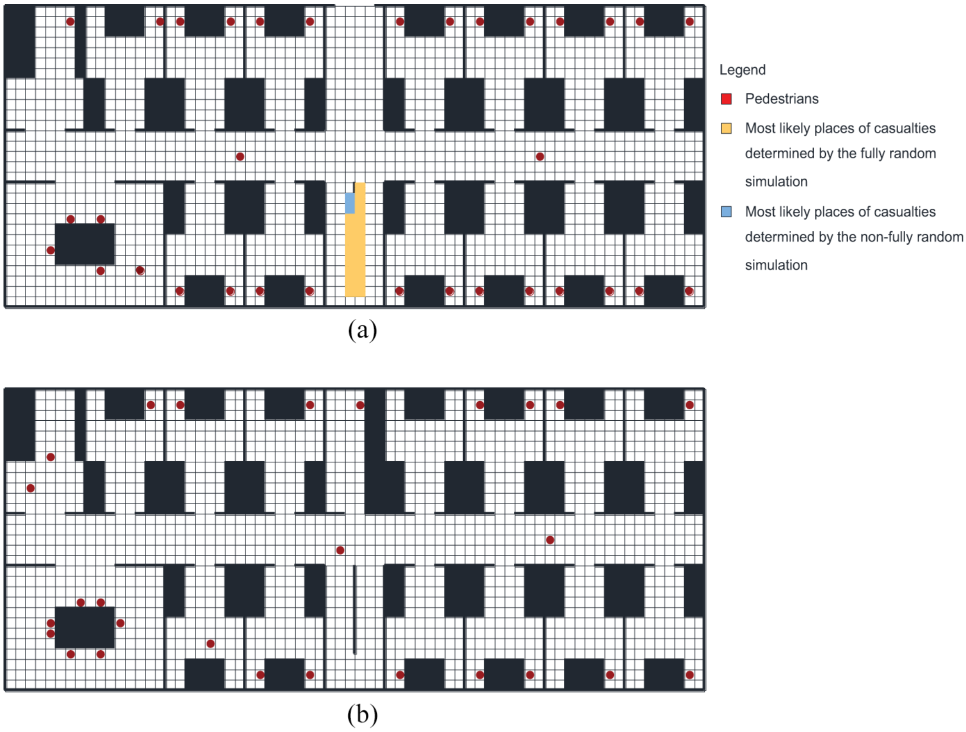

Figure 8. Initial distribution of the 60 pedestrians and most likely sites of casualties: (a) the first floor and (b) the second floor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to escape is plotted in Figure 8. The average motion velocity of the 60 staff is about $v = 1.5\,\mathrm{m/s}$, which means that the real time corresponding to one time step is approximately 0.27 s. Since experimental data of the emergency evacuation processes of this building are unavailable, the parameters in the pedestrian dynamics simulation are empirically determined as $J_s = 2$, $J_d = J_0 = 1$, $\beta = 10$, and $\alpha = 0.3$ for each particle (Burstedde et al., 2001; Li et al., 2018). In addition, only interactions between the pedestrians who are moving on the same floor and the distances between them are less than 4 m, that is, ten cells, are taken into account in the simulation.

Based on the obtained 100 occurrence times of damage and 100 distributions of damaged elements of the structure, a total of 100 simulations of the earthquake evacuation process of the building are performed using the proposed evacuation simulation model. As compared, based on the eighth occurrence time sample of damage shown in Figure 5 and the distribution of the damaged elements shown in Figure 7, a total of 100 simulations of the earthquake evacuation processes are also performed using the proposed model. For the case that the randomness of pedestrian dynamics, structural damage, and earthquake excitation are all considered, among the 100 simulations, there are 1 simulation that four pedestrians cannot successfully escape from the building due to serious injuries or deaths caused by damaged structural elements, 1 simulation that two pedestrians cannot successfully escape, 17 simulations that one pedestrian cannot successfully escape, and 81 simulations that all pedestrians successfully escape. The most likely sites of serious injuries or

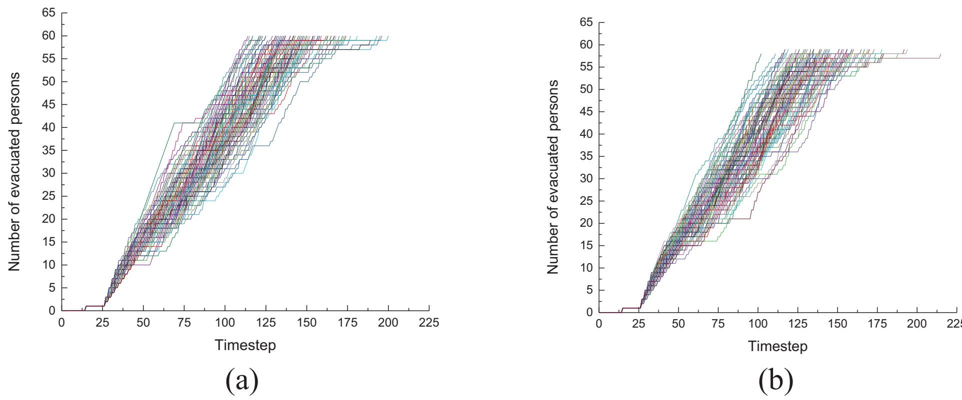

Figure 9. Number of evacuated persons versus time step: (a) the case that the three randomness are considered and (b) the case that only the randomness of pedestrian dynamics is considered.

deaths mainly occur in the stairwell and corridor on the second floor, as shown in Figure 8. Specially speaking, there are 12 simulations in which the sites of serious injuries or deaths occur in the stairwell (among them, there is a simulation that three pedestrians are seriously injured or dead in the stairwell and one pedestrian is seriously injured or dead on the first floor), 5 simulations in which the sites of serious injuries or deaths occur in the corridor on the second floor, and 2 simulations in which the sites of serious injuries or deaths occur in the corridor on the first floor. In contrast, for the case that only the randomness of pedestrian dynamics is considered, among the 100 simulations, there are 17 simulations that three pedestrians cannot successfully escape from the building due to serious injuries or deaths caused by damaged structural elements, 38 simulations that two pedestrians cannot successfully escape, and 45 simulations that one pedestrian cannot successfully escape. In the order words, there are casualties for each simulation in this case. The most likely sites of serious injuries or deaths for this case are the cells in the stairwell that are occupied by the damaged structural elements, as shown in Figure 8. The simulation results show that the mean casualty rate of the pedestrians in the building significantly decreases but the range of the most likely sites of casualties increases in the case that the randomness of pedestrian dynamics, structural damage, and earthquake excitation are all considered, compared with those in the case that only the randomness of pedestrian dynamics is considered. On the other hand, the randomness of structural damage and earthquake leads to the significant uncertainty of the pedestrian casualty.

For the two considered cases, the evacuation curves are obtained from the simulations and plotted in Figure 9. Note that the real TET is $T_E = t_p + n_E \Delta t$, where $t_p = 10\,\text{s}$ is earthquake early warning time, n_E is the number of the total time steps in a simulation, and $\Delta t = 0.27\,\text{s}$ is the size of each time step. It can be seen in Figure 9a that, in the case that the randomness of pedestrian dynamics, structural damage, and earthquake excitation are all considered, the slopes of the curves' bodies are almost constant (about 0.4). This implies that, for this case, the jamming does not occur in the earthquake evacuation and the flow of the pedestrians escaping from the exit is about one person per 0.8 s in the time period. Note that there are 24 simulations that the last several escaped pedestrians spend more time moving through the area close to the exit. They move around themselves in the last several time steps until their dynamic potential completely decays and then quickly escape from the building along the shortest path to the exit. This indicates that the head and group

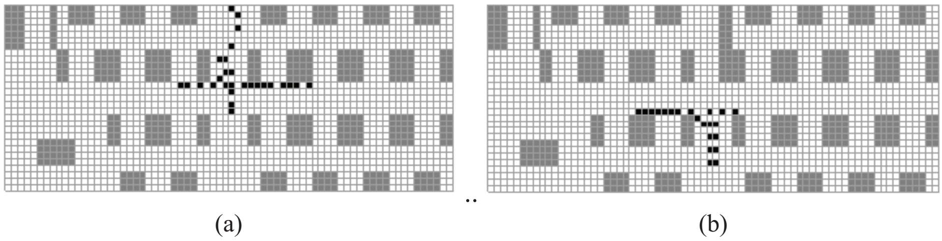

Figure 10. A picture of the status of pedestrian flow in a simulation: (a) on the first floor and (b) on the second floor.

behavior benefit the earthquake evacuation and dynamic potential without the head and group behavior may disturb the earthquake evacuation. For the case that only the randomness of pedestrian dynamics is considered, it can be seen in Figure 9b that the slopes of the curves' bodies as well as the head and group behavior are almost the same as those for the case that the randomness of pedestrian dynamics, structural damage, and earthquake excitation are all considered. This indicates that the randomness of the structural damage and earthquake excitation does not significantly change the essential features of the pedestrian dynamics, including the pedestrian flow and head and group behavior. Finally, it should be pointed out that the consideration of the randomness of the structural damage and earthquake excitation does not significantly increase the computational efforts of the simulations since the mean CPU times for the simulation are about 5003 and 4995 s, respectively.

For the case that the randomness of pedestrian dynamics, structural damage, and earthquake excitation are all considered, a transient state of the pedestrian flow at $T \approx 10 + 0.27 \times 40 = 20.8$ s in a simulation run, which is provided by the program, is plotted in Figure 10. It can be seen in Figure 10 that, in the corridors, pedestrians prefer to move along the walls and (dynamically varying) lanes of the motion of the pedestrians are formed. If the experiments show that the pedestrians tend to avoid walking close to walls and obstacles, then the proposed model can take into account this using the "wall potentials" (Nishinari et al., 2005).

Conclusion

A network-based fully random evacuation simulation model is proposed for simulating and analyzing the earthquake evacuation processes of multi-story buildings during earthquakes. The model solves the problem of the computational complexity of three-dimensional pedestrian dynamics simulation, couples the evacuation processes and structural damage processes, and takes account of the randomness of pedestrian dynamics, structural damage, and earthquake excitations. The model establishes a general framework for simulating earthquake evacuation of multi-story buildings under the consideration of the main factors affecting the earthquake evacuation processes, by which the related technicians can fast and effectively simulate the earthquake evacuation process of multi-story buildings. Based on the simulation results, the structural and architectural designers may design the optimal escape ways of new multi-story buildings during earthquakes such that the TETs are less than the allowed evacuation times defined by the seismic performance–based design codes or the casualty rates are reduced as much as possible. The simulation results can also be used by the technicians of urban disaster prevention and mitigation to predict the most likely places of the casualties for the existing multi-story buildings after earthquakes such that the casualties can be found as quickly as possible. An example of simulating and analyzing the evacuation process of a three-story office building during earthquakes demonstrates the effectiveness and use of the proposed model.

Finally, it should also be emphasized that there are currently two main limitations for the model: (1) The method for analyzing the seismic damages and damage fields of structures is still rough. The more refined stochastic finite element and collapse analysis of structures should be used to assess the seismic damages of the non-structural and structural elements and obtain the structural damage fields. (2) The model considers the relatively less human behavior. An agent-based cellular automata model should be developed to take into account more human behavior of pedestrians during earthquake evacuation.

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