EVACUATION ANALYSIS OF A COMMERCIAL PLAZA WITH CAFE MODEL

Weiguo Song, Yanfei Yu, Xuan Xu and Heping Zhang
State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, 230027, China

(Received 28 December 2004; Accepted 24 February 2005)

ABSTRACT

Along with the development of the society, more and more new-style buildings have appeared, of which the fire protection designs are sometimes beyond the requirements of existing national fire protection codes of China. Therefore, the performance-based fire protection design of buildings has been getting more and more chances of application. Evacuation analysis is one of the key problems in the performance-based design. In this paper, the performance-based design of a large commercial plaza is introduced, and a cellular automaton (CA) based evacuation model, i.e. CAFE model is used to analyze the efficiency of evacuation. The values of evacuation time obtained through the model are compared with those of the software EVACNET, and their differences are analyzed.

1. INTRODUCTION

For the past many years, the fire protection codes implemented in most countries are generally expressed in the form of instruction rules. These codes prescribe fire safety for a generic use or application. Fire safety is achieved by specifying certain construction characteristics, protection systems or limiting dimension without referring to how these requirements achieve the desired fire safety goal. This kind of fire protection code is called "prescriptive code" or "specification code".

Along with fast development of society and economy, more and more large-space complicated buildings come into existence. These buildings are different from traditional ones in function, material, structure, size and facilities, etc., bringing many new problems to fire protection. The prescriptive codes nowadays cannot fit all these new requirements. Thus the performance-based fire protection design has been adopted by more and more countries. Performance-based design is an alternative to traditional "prescriptive code" approach, and utilizes advanced engineering tools to provide solutions to complex fire and life safety problems or issues. Performance-based fire protection codes are being established gradually.

In performance-based design, guarantee of people's life safety is always the first aim. Therefore, performance-based evacuation design is one of the most important issues for the safety performance. Evacuation model is one of the key subjects of evacuation studies, and also is the mostly used technique in performance-based fire protection design.

At present, evacuation models can be divided into two categories: continuous models such as social force model, and discrete models such as lattice gas model and cellular automata model. Social force model presented by Helbing et al. [1-5] is a multi-particles self-driven model, a kind of multi-agent model. In this model, "social force" concept is introduced to represent the interactions, psychological and physical, between pedestrian and pedestrian, or pedestrian and environment. Because of its continuous nature, the model can subtly describe interactions of different levels. Thus it can obtain reliable simulation results and is suitable for cases with dense crowd. Its disadvantages are high calculation complexity, large resources consumed and long time cost.

Discrete model such as lattice gas model (or cellular automata model) [6-18] has been applied in the performance-based design since it has simple rules, costs little resource and time. During the process of evacuation, interactions between pedestrian and pedestrian, or pedestrian and environment (i.e. buildings) are constituted with attraction, repulsion and friction. These three forces play key roles in evacuation behavior, speed and efficiency. In former discrete models, attraction has been well described while repulsion and friction are still not represented quantitatively well.

Consequently we quantify calculation rules of friction and repulsion, based on the classic cellular automata model [17,18], introduce a new CA model CAFE (Cellular Automata with Forces Essentials). The model can obtain comparative results with social force model in simulating pedestrian behaviors, evacuation velocity and "faster is slower" [2,4] effect which occur in actual evacuation, but with the similar calculation efficiency as normal CA model or lattice gas model, much better than that of social force model. As a case study, we apply CAFE model in the performance-based design of a large commercial plaza. The simulation results of CAFE are compared with those of EVACNET, a widely used commercial software, and their differences are discussed.

2. CAFE MODEL

In traditional CA or LG models, a lattice is used to present the field concerned; each site on the lattice can be a pedestrian, a part of building or empty site. Considering the average size of a pedestrian, the size of a lattice is 0.4 m long and 0.4 m wide, which is related to the human body dimension. Each pedestrian walks to one of his four adjacent lattices with some probabilities or stay still, as shown in Fig. 1 (down is the forward direction). If the probabilities corresponding to the four walking directions are not equal, it is called a biased walk, and pedestrians in the model are called biased walkers.

In CAFE model, we consider in detail the interactions between pedestrian and pedestrian, and pedestrian and environment during evacuation. Repulsion and friction are introduced into basic CA model, and are parametrically quantified.

Repulsion occurs when a pedestrian is near other pedestrians or walls, as shown in Fig. 2. The result of repulsion is the action of slowdown and avoiding. If all the pedestrians involved in the conflict choose stay still with probability *r*, the moving probability *p* for each pedestrian is shown in equation (1).

$$p = (1 - r)/m \qquad (1)$$

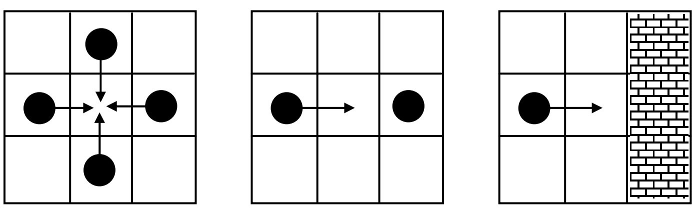
Here $m(m \geq 2)$ is the number of pedestrians involved in the conflict, *r* the stay probability, *p* the moving probability.

In an emergent evacuation, friction is another key factor impacting evacuation behaviors (Fig. 3). The result of friction is the slowdown when two pedestrians, or a pedestrian and wall, touching each other. In order to quantify the effect of friction, we introduce a friction probability *f* to represent the probability with which all pedestrians involved in the conflict choose stay still, then the moving probability *p* of each pedestrian is shown in equation (2).

$$p = 1 - f \qquad (2)$$

(a) Four directions walk and its walking probabilities (b) Walk without the back step

Fig. 1: Walk strategy of a pedestrian



(a) (b) (c)

Fig. 2: Occurrence of repulsion

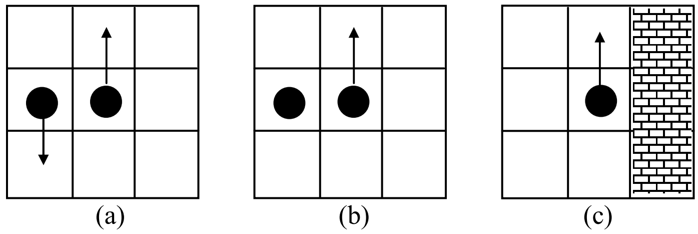


Fig. 3: **Occurrence of friction**

The repulsion probability is related to the relative speed. Furthermore, there is an endure threshold for the pedestrian, if the relative speed is greater than the threshold, the pedestrian always avoid it. Thus Sigmoid function is reasonable to express repulsion probability, as shown in equation (3):

$$r \equiv \frac{1-e^{-\alpha V}}{1+e^{-\alpha V}} \quad (3)$$

where V is the relative speed, $\alpha \in [0,\infty]$ is the hardness degree.

The friction probability f is calculated with equation (4).

$$f \equiv \theta * V \quad (4)$$

where $\theta \in [0,1]$ is the friction coefficient, reflecting the roughness of pedestrian and wall.

At each time step, the CAFE model evolves as follows:

1) Search possible moving directions considering the position of exit;
2) Calculate repulsion and friction, obtain the moving probability to each direction;
3) Update the position of each pedestrian.

3. GENERAL SITUATION OF THE COMMERCIAL PLAZA

The concerned commercial plaza owns five aboveground floors and one underground floor. It has a total building area of 265,000 m^2, of length 480 m and width 200 m. It consists of seven separate shopping malls that deal with entertainment, food, daily goods, digital products, and building materials, etc. The underground floor is for storage, facility rooms and parking lots. At the central part of the plaza, there located a two-story high and partly three-story high atrium, which joins all the sub-buildings into a whole plaza.

According to relevant fire protection codes of China [19], there exists some problems with the commercial plaza:

a. The area of the atrium (23,624 m^2) is much larger than 4,000 m^2, the maximum allowed area of fire compartment.

b. The largest evacuation distance in the atrium is 100 m, much larger than the 30 m prescribed maximum distance.

c. Some of the safety exits of separate shopping malls are opened into the atrium, not outside.

4. PERFORMANCE-BASED RE-SOLUTION

In order to solve these problems, the designers proposed an idea of "sub-safe atrium". In all the retail cells and separate shopping malls near the atrium, independent fire protection equipment are installed respectively, and the fire smoke is prevented to overflow into the atrium through the control of mechanical smoke exhaust system, sprinkler system and fire compartmentation. At the same time, there are no commercial activities and no fuel load in the atrium area since it is the main passage. Moreover, water sprinkler system is equipped in cloister of the atrium and natural smoke exhaust windows are designed on the top of the atrium. Thus the probability of fire occurrence is small enough in the atrium that the atrium can be considered as a comparatively safe area that guarantees enough time for evacuation.

We calculate the evacuation times when crowd escape into the atrium and escape outside of the building using software SafeGo based on the CAFE model. We also compare the evacuation results with those of smoke movement and fire spread to analyze evacuation safety.

It is obvious that the three problems mentioned above are all related to evacuation time calculation.

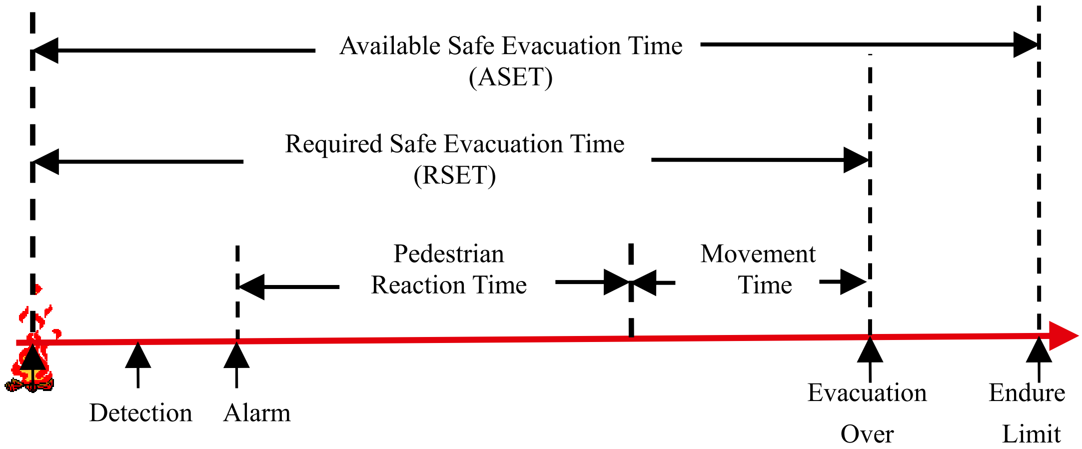


Fig. 4: Evacuation time line

5. EVACUATION ANALYSIS

We usually use available safe evacuation time (ASET) and required safe evacuation time (RSET) to evaluate safety performance (Fig. 4). ASET is influenced by the performance of fire protection systems and fire spread, while RSET is connected to pedestrian psychology, behavior and crowd density. If ASET is larger than RSET, the evacuation in the building is considered safe [20].

RSET or t_E is constituted of fire detection time (t_{alarm}), pedestrian reaction time (t_{resp}) and movement time (t_{move}):

$$RSET = t_E = t_{alarm} + t_{resp} + t_{move} \quad (5)$$

t_{move} is obtained through software SafeGo based on the CAFE model. The widths of exits are calculated by the efficient width model presented by Pauls [21], i.e. widths of exits and stairs should be shortened considering the boundary effect. When the boundary is a wall, the boundary effect width is 150 mm, while the boundary effect width of an armrest is 90 mm.

t_{resp} is obtained through BSDD240 [22]: when onsite broadcast is used, t_{resp} is less than 1 minute; when recorded broadcast is used as alarming, t_{resp} is valued around 3 minutes; when normal alarm bell is used, t_{resp} is more than 4 minutes. Since the shopping mall installs onsite broadcast system, t_{resp} is 60 s.

t_{alarm} is 60 s according to fire smoke calculation. When the smoke cumulated below the ceiling covers the smoke detector, the smoke detector is considered being triggered. The calculation error is taken into account in the safety margin between ASET and RSET.

The number of people is provided by the designer according to the national fire protection codes, in which the number of people is calculated by the building area multiplying the area-reduction coefficient and conversion coefficient.

Based on the above conditions and parameters, we calculate t_{move} by the CAFE model, and obtain the total evacuation time RSET. The free-walk velocity or the maximum velocity of the pedestrian is set to 1 ms^{-1}.

Evacuation processes of three different cases are simulated: no fires, fire scenario1 and fire scenario 2. Demonstrations of different fire scenarios are shown in Fig. 5. In fire scenario 1, fire occurs at the left part of the atrium and blocks exit 1 there, so pedestrians around there have to use other exits. While in fire scenario 2, fire occurs at the upper part of the atrium. Exit 2 is disabled, so people there have to escape through other exits.

Simulation results at different moment of evacuation are shown in Figs. 6-17. Gray area represents area where the crowds evacuate, while white dots represent pedestrians. We can observe the jamming phenomena around the exits, as well as the arch distribution of crowd.

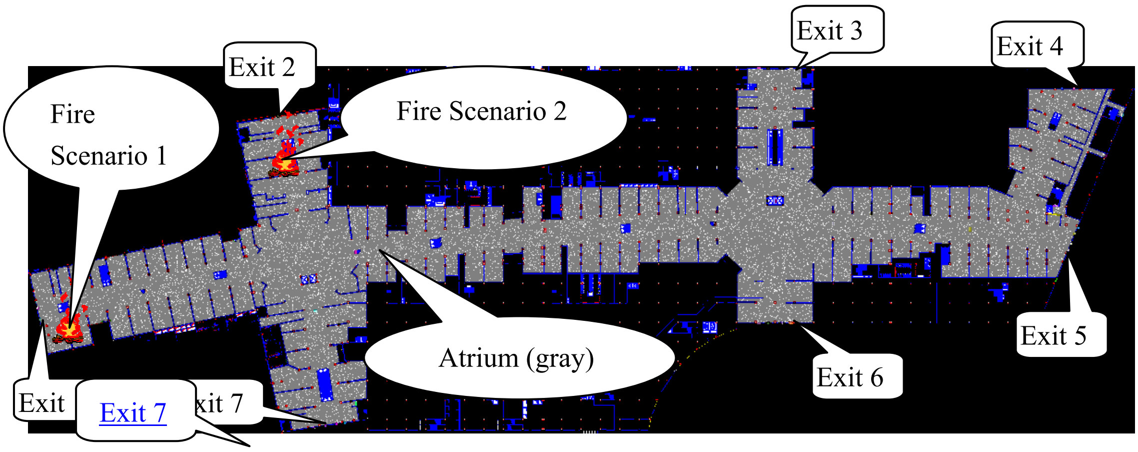


Fig. 5: Different fire scenarios in the atrium 1st floor

Fig. 6: Evacuation in the atrium 1st floor with no fires (0 s)

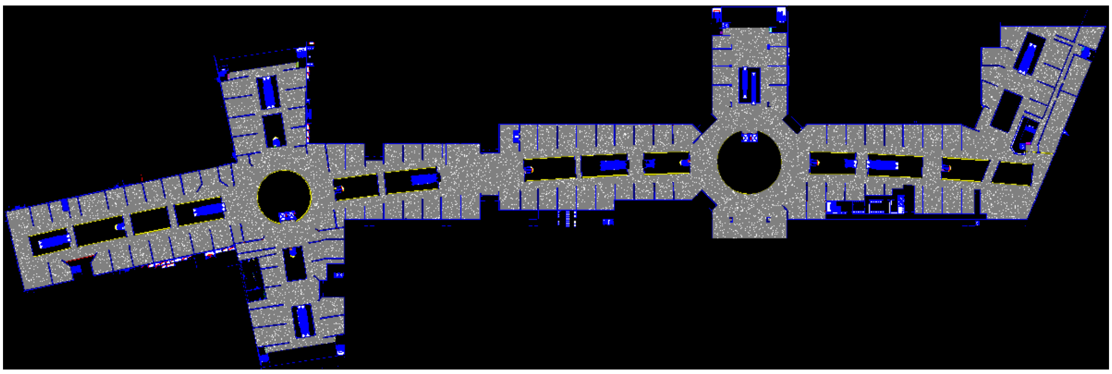


Fig. 7: Evacuation in the atrium 2nd floor with no fires (0 s)

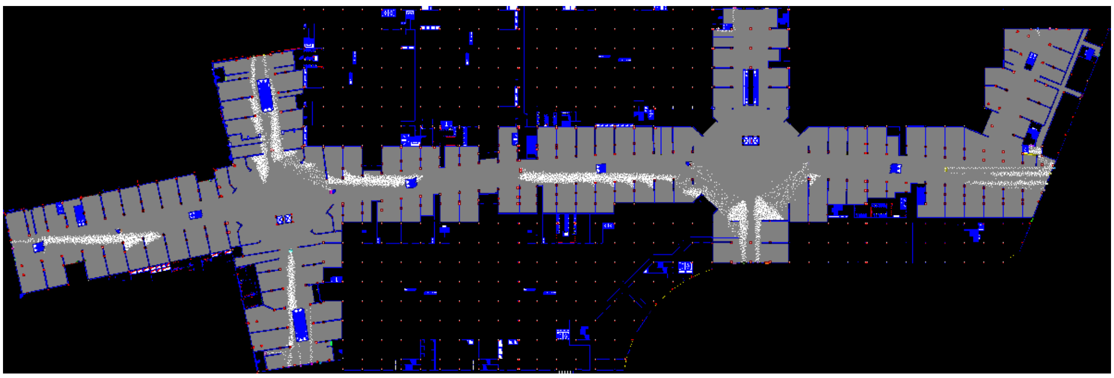


Fig. 8: Evacuation in the atrium 1st floor with no fires (120 s)

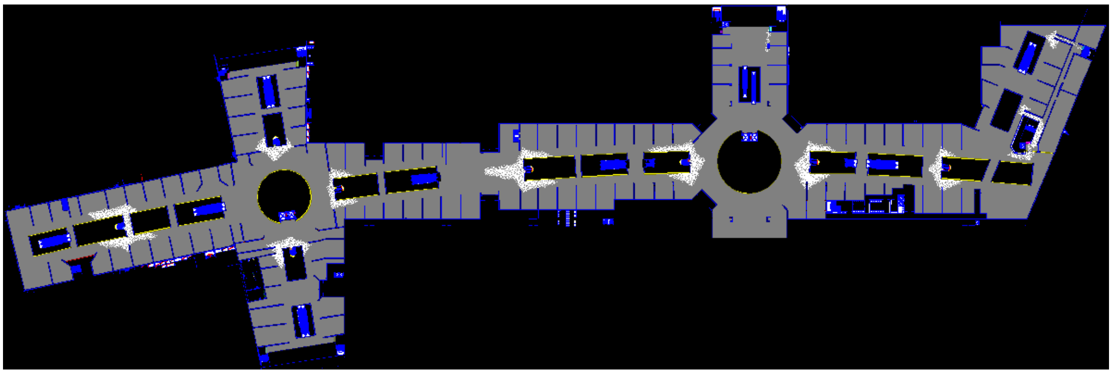


Fig. 9: Evacuation in the atrium 2nd floor with no fires (120 s)

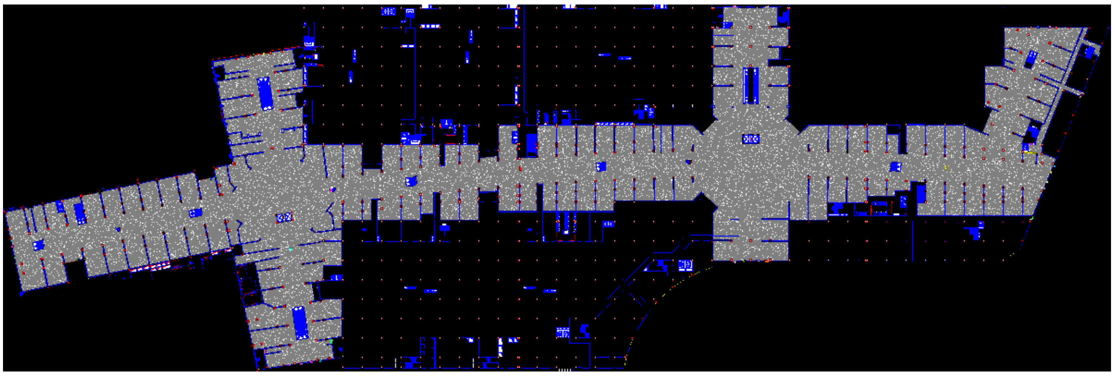


Fig. 10: Evacuation in the atrium 1st floor for fire scenario 1 (0 s)

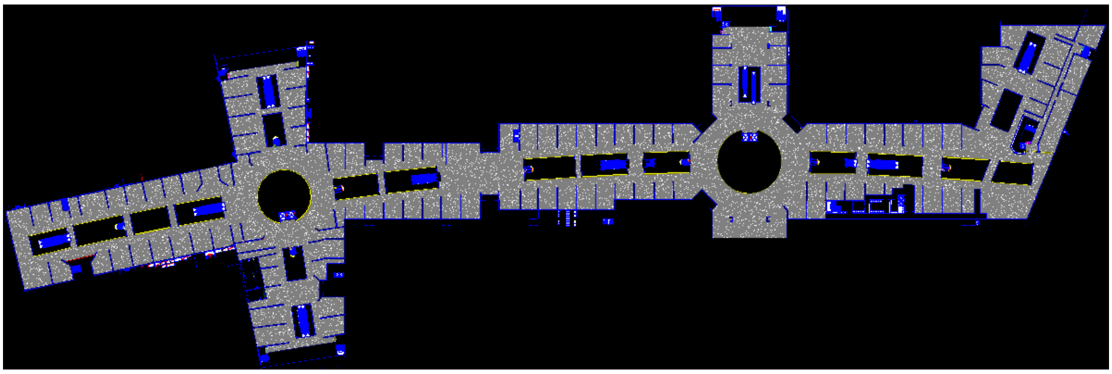


Fig. 11: Evacuation in the atrium 2nd floor for fire scenario 1 (0 s)

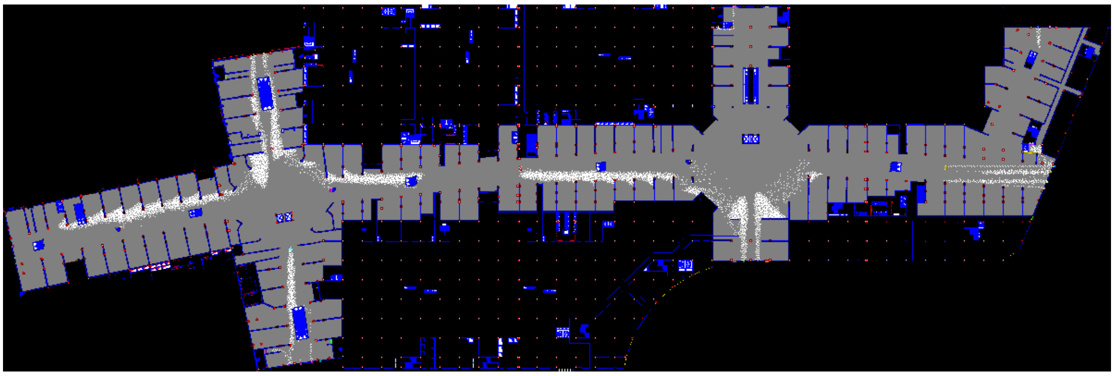


Fig. 12: Evacuation in the atrium 1st floor for fire scenario 1 (120 s)

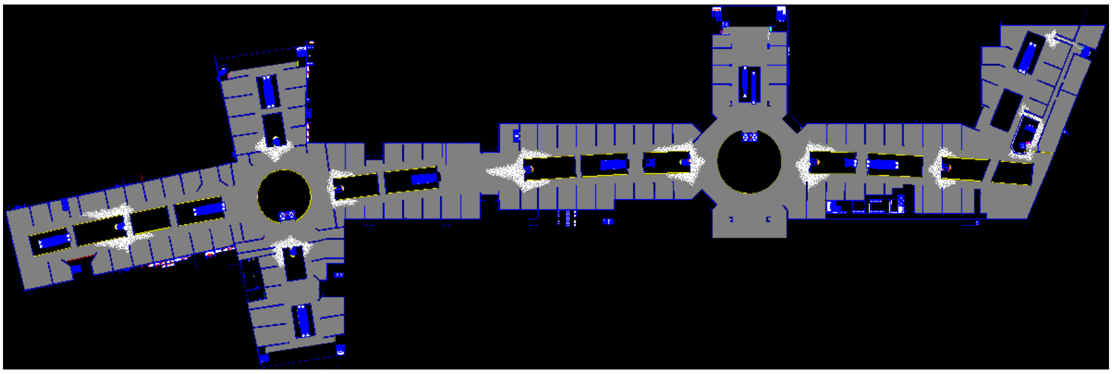


Fig. 13: Evacuation in the atrium 2nd floor for fire scenario 1 (120 s)

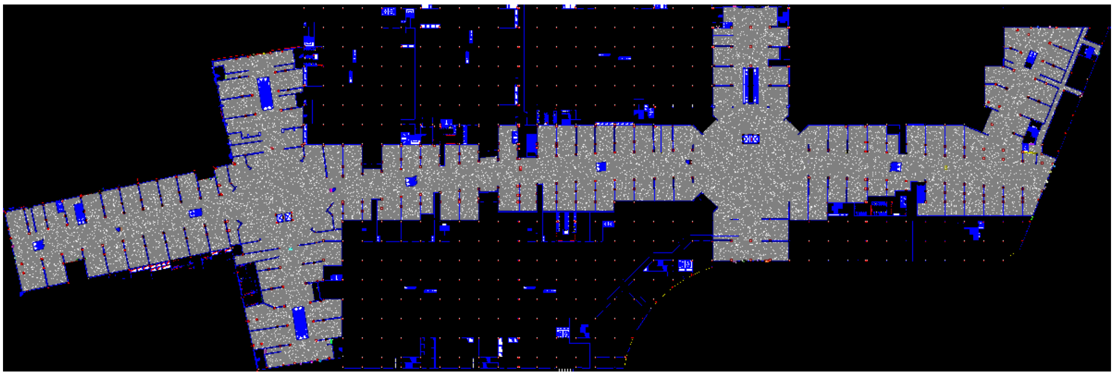


Fig. 14: Evacuation in the atrium 1st floor for fire scenario 2 (0 s)

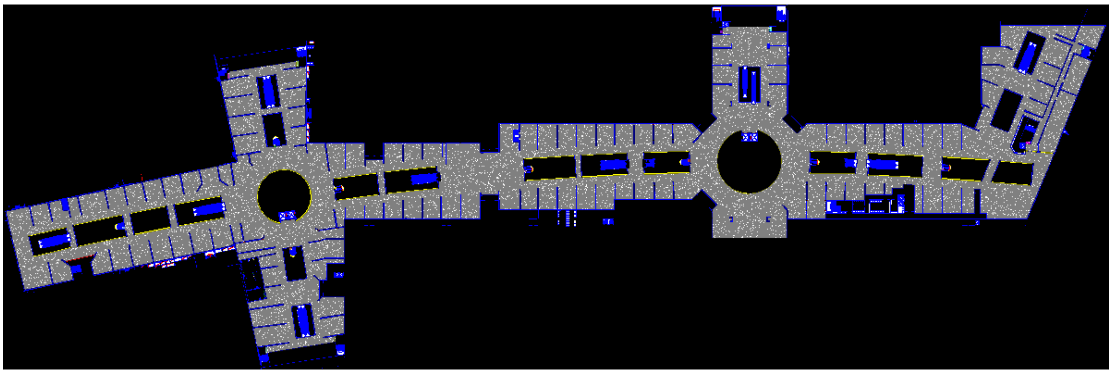


Fig. 15: Evacuation in the atrium 2nd floor for fire scenario 2 (0 s)

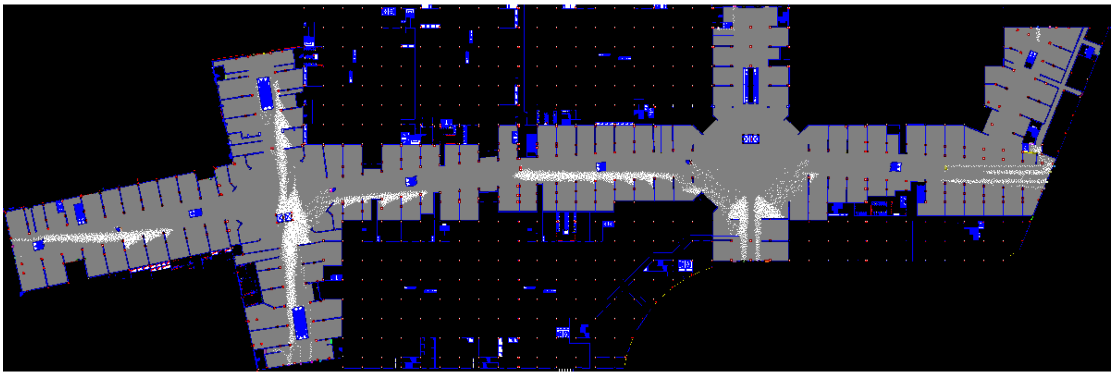


Fig. 16: Evacuation in the atrium 1st floor for fire scenario 2 (120 s)

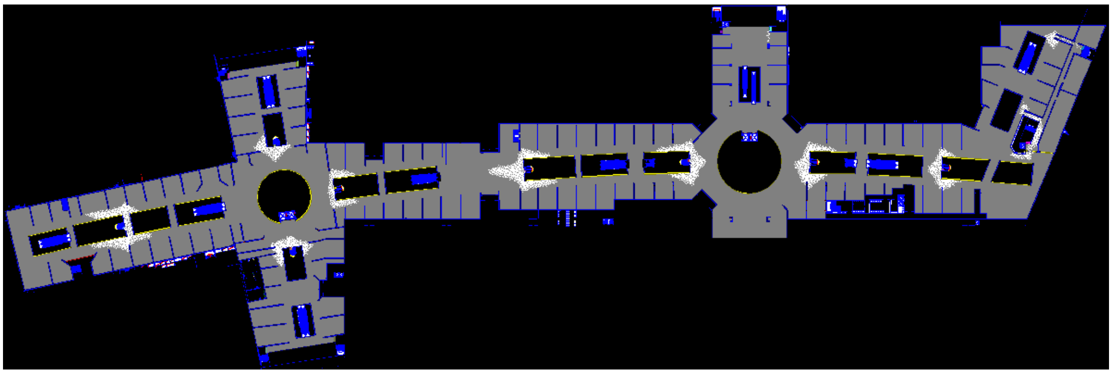


Fig. 17: Evacuation in the atrium 2nd floor for fire scenario 2 (120 s)

Table 1: Evacuation time (RSET) and movement time of the whole atrium

Floor	by EVACNET (s)		by CAFE model (s)	
	RSET	Movement time	RSET	Movement time
1st floor no fires	1135	1015	1385	1265
2nd floor no fires	1065	945	730	610
1st floor scenario 1	1255	1135	1653	1533
2nd floor scenario 1	1065	945	712	592
1st floor scenario 2	1135	1015	1490	1370
2nd floor scenario2	1065	945	799	679

The calculation results of CAFE model are compared with software EVACNET. EVACNET is a user-friendly interactive computer program that models building evacuations. The program accepts a network description of a building and information on its initial contents at the beginning of the evacuation. From this information, EVACNET produces results that describe an optimal evacuation of the building. Each evacuation is optimal in the sense that it minimizes the time to evacuate the building. People are evacuated as quickly as possible.

Evacuation Time (RSET) and movement time results are shown in Table 1. It is found that calculation results of CAFE model are generally consistent with those of EVACNET [23] considering the allowable extent of engineering error. The former is a little larger in the 1st floor is because CAFE model considers more delicate interactions: friction and repulsion effects which reduce the evacuation efficiency; while its results are smaller in the 2nd floor is because EVACNET forces pedestrians in rooms near the exit escape into corridor first than those in rooms far from the exit when the corridor is full. This kind of queuing effect increases the evacuation time of pedestrians far from the exit, for example those in the 2nd floor. However, in an emergency evacuation, queuing effect near the exit is not as regular as that in normal situation, and the crowd becomes uncoordinated [2]. From this point of view, CAFE model is more like a social force model [2,4].

6. CONCLUSION

At present, codes for performance-based fire protection design still have not come into being in China, whereas more and more developments have been obtained in the study and application of performance-based design. As one of the key contents of performance-based design, evacuation analysis is a complex issue corresponding to the psychological behaviors, response abilities of pedestrians, and environmental conditions (i.e. fire) and buildings structure. To consider these factors, we develop a new evacuation model, CAFE model, in which the friction, repulsion and attraction between pedestrians or between pedestrian and environment are quantified by means of probability parameters. Therefore CAFE model is expected to simulate evacuation in detail. Furthermore, in the view of application, CAFE model has higher calculation speed and simple rules, and thus more suitable for large-scale evacuation calculations.

To check its ability, CAFE model is applied in analyzing evacuation performance of a large commercial plaza. It is found that similar results are obtained to those of software EVACNET, indicating CAFE model is also reliable for evacuation analysis. It is also shown that the calculation results of CAFE model are generally a little larger or more conservative than those of EVACNET. The considering of interactions in evacuation might be a reasonable explanation. And it also shows a slight disadvantage of EVACNET: unreal simulation of evacuation queuing when the main corridor is full.

As a new frame structure evacuation model, CAFE can be used to reveal basic behaviors of evacuation through expansion and improvement of simulation rules of friction, repulsion and attraction. It can also be applied to the analysis and simulation of evacuation in different scenarios.

ACKNOWLEDGEMENT

The work is supported by the National Natural Science Foundation (No. 50320120156, 50323005) and Key Technologies Research and Development programme (No. 2004BA803B03)

REFERENCES

1. Weicheng Fan, Jinhua Sun and Shouxiang Lu, Fire risk evaluation methodology, Beijing: Science Press of China (2004).

2. D. Helbing, I. Farkas and T. Vicsek, "Simulating dynamical features of escape panic", Nature, Vol. 407, pp. 487-490 (2000).

3. D. Helbing, J. Keltsch and P. Molnar, "Modelling the evolution of human trail systems, Nature, Vol. 388, pp. 47-50 (1997).

4. D. Helbing and P. Molnar, "Social force model for pedestrian dynamics", Physical Review E, Vol. 51, pp. 4282-4286 (1995).

5. D. Helbing, F. Schweitzer, J. Keltsch and P. Molnar, "Active walker model for the formation of human and animal trail systems", Physical Review E, Vol. 56, pp. 2527-2539 (1997).

6. M. Muramatsu and T. Nagatani, "Jamming transition in two-dimensional pedestrian traffic", Physica A, Vol. 275, pp. 281-291 (2000).

7. M. Muramatsu and T. Nagatani, "Jamming transition of pedestrian traffic at a crossing with open boundaries", Physica A, Vol. 286, pp. 377-390 (2000).

8. Y. Tajima and T. Nagatani, "Scaling behavior of crowd flow outside a hall", Physica A, Vol. 292, pp. 545-554 (2001).

9. Y. Tajima, K. Takimoto and T. Nagatani, "Scaling of pedestrian channel flow with a bottleneck", Physica A, Vol. 294, pp. 257-268 (2001).

10. Y. Tajima and T. Nagatani, "Clogging transition of pedestrian flow in T-shaped channel", Physica A, Vol. 303, pp. 239-250 (2002).

11. T. Nagatani, "Jamming transition in the traffic-flow model with 2-level crossings", Physical Review E, Vol. 48, pp. 3290-3294 (1993).

12. T. Nagatani, "Jamming transition in a two-dimensional traffic flow model", Physical Review E, Vol. 59, pp. 4857-4864 (1999).

13. T. Nagatani, "Dynamical transition and scaling in a mean-field model of pedestrian flow at a bottleneck", Physica A, Vol. 300, pp. 558-566 (2001).

14. Tao Chen, Weiguo Song, Weicheng Fan and Shouxiang Lu, "Jamming transition of pedestrian evacuating flow in crossing exit", In: P. Huang, Y. Wang, S. Li and X. Qian (editors), Progress in Safety Science and Technology, Beijing: Science Press, Vol. III, pp. 507-512 (2002).

15. D. Helbing, M. Isobe, T. Nagatani and K. Takimoto, "Lattice gas simulation of experimentally studied evacuation dynamics", Physical Review E, Vol. 67, article no. 067101 (4 pages) (2003).

16. C. Burstedde, K. Klauck, A. Schadschneider and J. Zittartz, "Simulation of pedestrian dynamics using a two-dimensional cellular automaton", Physica A, Vol. 295, pp. 507-525 (2001).

17. A. Kirchner and A. Schadschneider, "Simulation of evacuation process using a bionics-inspired cellular automaton model for pedestrian dynamics", Physica A, Vol. 312, pp. 260-276 (2002).

18. A Kirchner, K. Nishinari and A. Schadschneider, "Friction effects and clogging in a cellular automaton model for pedestrian dynamics", Physical Review E, Vol. 67, article no. 056112 (10 pages) (2003).

19. http://www.fireren.com/down/openarticle.asp?id=4 19

20. D.W. Stoup, Using performance-based design techniques to evaluate fire safety in two government buildings, NIST, Gaithersburg (1998).

21. J. Pauls, "Effective width model for crowd evacuation", Sixth International Fire Protection Seminar, Karlsruhe, West Germany, 1982; In: J. Templer (editor), The staircase, Massachusetts Institute of Technology, Cambridge, MA (1992).

22. British Standards Institution, Draft British Standard BSDD240 Fire safety engineering in buildings, Part 1: guide to the application of fire safety engineering principles, British Standards Institution (1997).

23. http://www.ise.ufl.edu/kisko/files/evacnet/