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Occupant evacuation and casualty estimation in a building under earthquake using cellular automata

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HIGHLIGHTS

- We model the emergency evacuation in a building using cellular automata method.
- Evacuation and building collapse simulations are coupled for casualty estimation.
- Casualty estimation is analytical rather than experiential or statistical.
- Occupant distribution, gathering, stranding, locations of casualties are calculated.
- Fragility of casualty and death induced economic loss are calculated.

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ABSTRACT

Knowledge of occupant evacuation process in a building presents engineers with an efficient way of testing the rationality of the building design before construction. Meanwhile, it benefits to the occupant casualty estimation in the building under earthquakes, which has been an essential problem in the performance-based earthquake engineering methodology. The cellular automata model is adopted to simulate the occupant movements in the building. The factors including the behaviors of directional moving to exits, directional moving with crowds, and the competitive phenomenon to a position are included in the model. Evacuation processes at different regions of the building containing room, corridor and staircase are considered and effects of model parameters, competition, exit width, and occupant density are studied. The building collapse under earthquakes is simulated by explicit finite element method. The occupant casualties in an earthquake are evaluated by coupling the building collapse simulation and evacuation process simulation with time and space synchronization. A casualty occurrence criterion is defined using relative displacement. Comparing with existing methods, the presented method can provide estimations on occupant evacuation process and occupant casualties in a more accurate way and provide after-earthquake occupant casualty distributions in the building. Fragility functions of casualty and death caused economic loss are also provided.

1. Introduction

It is very important from an engineering viewpoint to predict the time taken to evacuate a building through the analysis of occupant evacuation. To check the bottlenecks of the building, in which rapid evacuation means life or death, is beneficial

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to designers to improve the construction. Meanwhile, the simulation of occupant evacuation process in a building is a promising method to implement the more rational and quantitative estimation on occupant casualties in a building under hazard loadings.

In the most cases of the economic loss during hazards, the economic loss caused by occupant casualty provides a major contribution to the total loss. The calculation of casualty caused economic loss is relative directly to the casualty number. The recent observations illustrate that the occupant dynamics in the hazards, i.e., the movements of the occupants, have effects on the casualty. There is an example that about 2300 teachers and students evacuated from two buildings with four stories and five stories only within 96 s in the Sangzao Middle School in the 2008 *M*8.0 Wenchuan earthquake, China. This indicates that if the occupant dynamics are not considered, the result of estimation on the casualty number could be far from the real state in some situations. Due to the difficulties in the field test, numerical simulation of evacuation process from a dangerous region to a safe region has been attracting more and more attentions for occupants. Basically, present main methods include social force models [1,2], continuum models [3,4], agent-based models [5,6] and cellular automata models. Among these methods, there has been a great interest in studying cellular automata models in order to simulate evacuation process because of its inherent virtues.

In the last decade, cellular automata models for occupant dynamics have been widely studied [7–15]. These studies are focused on the evacuation time, occupant behaviors and a variety of phenomena in the evacuation process. These studies illustrate that cellular automata models are an appropriate choice, since, in spite of its computational simplicity and efficiency, they are able to model individual and collective behaviors of occupant dynamics in emergency cases and complex situations. However, almost all the studies focus on the evacuation in fire hazard cases. In addition, the studies on simulation of evacuation process from a whole building with several stories are insufficient, which may provide useful information for the high-rise building designs [16–18]. According to the study in Ref. [17], parameters influencing the evacuation efficiency can be categorized into four main categories: (1) physical characteristics of building; (2) behavioral characteristics of occupant; (3) physiological characteristics of occupant, and (4) hazard loading characteristics of environment. The existing studies for fire hazard cases treat the fourth category as fire; and treat the first category, i.e. the building, as a fixed non-deformable obstacle without actual material and geometrical nonlinear characteristics; the building cannot be damaged or collapse in these methods even the fire is serious enough. There is an example of the attack on the WTC in New York in 2001, in which the building collapse is the dominated factor among several factors (e.g. fire, etc.) that affect the evacuation and 2800 deaths. Hence, these studies are suitable to small fire events, but could not be suitable to the cases with building collapse induced by disaster loadings, such as the serious fire, attack, or earthquake.

Earthquake that is one of the main hazard loadings has caused lots of building collapses and threaten the safety of human beings. Occupant casualty estimation under earthquakes is an essential issue because it is useful to determine pre-event performance-based building design, after-event search and rescue guidelines and total loss estimation, as well as estimate on the potential impact of the death numbers on the social society. Most of the present casualty estimation studies deal with a macro prediction for an area level, such as a large region covering many buildings, a city or a county, which use experiential or statistical results for the entire area. Detailed literature reviews on this type of studies can be found in Ref. [19]. Some assumptions are usually adopted in these studies, e.g. there is a strong correlation between the casualties and the earthquake magnitude as a function of population density [20], and the HAZUS software [21] is based on that there is a strong correlation between building damage degrees and casualties. Actually, the casualty estimations involve many uncertainties since the casualty numbers vary greatly from one area to another because the data for deriving the correlations are usually poorly documented, and maybe obviously different in several aspects including building types (e.g., different types, and same type but with different configurations), building codes in different times and countries, soil and foundation conditions, material properties, and earthquake loadings, etc. [22,23]. Although there are significant uncertainties, these methods may be acceptable predictors of earthquake effects for a large group of buildings. They are, however, not suitable predictors for a specific building.

The building-specific estimation is essential for some cases and also definitely more accurate than the above-mentioned methods if it is used for an area because one by one building can be calculated. The HAZUS software developed its Advanced Engineering Building Module (AEBM) to overcome the problem [24,25]. The AEBM uses building-specific damage fragility functions instead of the general ones, but the estimation on casualties also contains human experiences and uncertainties. In the recent study work, Furukawa and Ohta [26], Furukawa et al. [27] predicted the casualties in the collapse of masonry buildings induced by earthquake. In their studies, a distinct element method was used for building collapse simulation and casualty was estimated due to impact loading and compression force by the falling building components. The casualty number is considered proportional to the ratio of converging area by the fallen building components to the initial floor slab area. However, these studies do not consider the occupant dynamics in the building, which may result in an inaccurate estimation on the casualties since the occupants are generally not uniformly distributed at the building collapse moment. Moreover, few studies provide the estimation on stranded occupant distributions in a building after earthquakes.

This paper proposed a method that can provide estimations on occupant evacuation process, casualty and economic loss in a building under earthquakes. The paper is organized as follows: A cellular automata model coupling with parameter study for occupant evacuation process simulation is presented in Section 2. The numerical simulation of building collapse is described in Section 3. Occupant casualty estimation method is provided in Section 4. Casualty fragility and loss estimation are presented in Section 5. Numerical examples are presented to illustrate the proposed method in Section 6. Known limitations of the proposed method are summarized in Section 7. Some conclusion remarks complete the study.