

Evaluation of the Evacuation of Essential Buildings: Interaction of Structural and Human Behaviour through Nonlinear Time-History Analysis and Agent-Based Modelling

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Abstract. In this article, a performance assessment of the evacuation system is established for educational buildings. Structural and geotechnical information of the building is collected and introduced into a database. A similar procedure was realized for the information related to the occupants. Using this information, a) the structural fragility and localized collapse were determined and b) the interaction of the person with the partial collapse was established. For the first aspect, nonlinear time history was used, and for the second, the agent-based modeling was applied to recreate the reaction of people that face the micro collapse. Therefore, the important results of this evaluation are: 1) To localize collapsed beams and columns that make inoperable evacuation routes, 2) to localize bottleneck areas that people concentration during evacuation, and 3) quantification of affected people, in terms of persons caught up in the building that cannot evacuate.

1. Introduction

In the period 1995-2015, more than 600,000 million people have died in natural disasters, economic losses are around 300,000 million dollars annually and 10% of natural disasters are of geophysical origin, all of the above in the five countries most affected by this type of disaster [1].

Now, the causes of the collapse of a building are: The breach of the specifications by the developers, corruption, inadequate design, defective construction methodology, inadequate supervision, change of use of buildings and low maintenance. Each cause is more recurrent according to the level of professionalism and development in each part of the world [2].

However, apart from structural concern, the researchers perform calculations to evaluate safety parameters in evacuation of establishments. Usually, these calculations are focused on architectural details, such as the location of the doors and reduce the time of arrival at an exit. However, they are not always reliable because evacuation drills are conducted in controlled environments; Here, for example, does not provide more complex factors such as emotions of people facing emergencies such as panic, fear and stress [3].

Currently there is commercial software for the evaluation of seismic performance of individual buildings that allow predicting the response of structural damage. The programs are applicable to new or existing buildings, and can be used to: (1) evaluate the probable performance of a building, (2) design new buildings providing the desired performance, or (3) improve the seismic design of buildings existing [4]. Likewise, software for modeling agents, which allow occupant profiles to be made, making it possible to simulate evacuations of buildings in case of emergencies [5].



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This research has integrated the structural and human behavior of an educational institution during various seismic events. For the first, structural performance was evaluated by nonlinear time-history analysis. For the second, the existing capacity of the institution was taken to represent the behavior of people using the methodology of decision making. Finally, the efficiency of the evacuation system is questioned based on the results obtained.

2. Method

The evaluation of the evacuation system of a building has two important parts. First, structural behavior was analyzed by nonlinear time-history analysis. This allows us to evaluate the dynamics of the structure considering the inelastic behavior of the elements, through the use of standardized seismic registers. Second, user behavior was analyzed using agent-based modeling. This consists of modeling an agent, in which certain behaviors can occur in order to observe complex effects of the flow of people in a given environment. Finally, both structural and human behaviors interact together to obtain system results as a whole.

2.1. Data collection

A study of an establishment of interest that concentrates a large number of people is carried out. These can be hospitals, municipalities, educational institutions and others. From these categories an essential building is chosen, to begin with the compilation of building data; such as, structural plan, recognition of structural elements, detailed, etc. The building can be a structural system of reinforced concrete with structural walls and porches.

For the elaboration of the agents that will be used in the simulation, physical and psychological variables are taken into account. For the correct use of these variables it is proposed to make a recording of the evacuation drill of the building selected for the analysis. For physical variables is correct to take account the position of the agents, speed, vision, width and height. In the same way, for psychological variables, reaction time, acceleration time, persistence time and comfort distance are indispensable for the analysis.

With the aforementioned variables, the agents are programmed to make decisions during the simulation (decision-making methodology). This programming is done in commercial software, such as Pathfinder.

2.2. Definition of scenarios

The presence of people in the building was determined according to the number of classes that are being taught at certain times. It is proposed in this methodology 3 different schedules. For example: 7am, 12pm and 7pm. In addition, seismic records representative of the history for the area under study are identified. This data will be used for the Analysis of the response history, since a set of soil movement records selected and modified correctly is required as input.

2.3. Structural analysis

The purpose of the structural analysis is to obtain the distribution of the stresses and the corresponding displacements of the structure subjected to a given load. It can be calculated by using appropriate methods that express nonlinear analyzes such as Pushover, History Time, Incremental Analysis, etc. There are Software for the structural analysis of buildings with 3D modeling and visualization tools such as ETABS or SAP2000.

2.4. Human analysis

In addition to the way agents act, start and exit points must also be programmed for evacuation. Clearly this type of activity is not the cream of an agent who can make decisions according to situations, but it helps to keep the modeled evacuation under control. Agents will be generated by zones. The programmer can define whether these zones are interconnected with each other or the accesses are blocked at certain outputs. In this case the zones were created according to the distribution of halls, passageways and among other places they are delimited by zones.

3. Results

3.1. Evacuation drill

The recording made on May 31, 2019 provided important results to perform a more realistic evacuation simulation. These results were decided to separate them into physical and psychological.

On the part of the physical results, it is emphasized that the capacity of the people during the drill is the same as the one in the database of the study center. Also, the average speed of the people was 1.3 m/s. There were no people with any complications to move, however, during the drill it started to rain so some people decided to go slower because of the fear of slip of, preventing a faster speed than the one described. The turning radius of people was 0.65 m. The average height of the people in the drill was 1.70 m. This feature affects directly the range of vision, which it was found as 3 m.

On the other hand, in terms of the psychological, people had a reaction time of 0.8 s. facing any external stimulus they faced. These stimuli were mostly closed doors and accesses, imminent clash with other people and perception of great congestion of people. At the time of evacuation, people who realized that the congestion of people was high took 2 seconds to decide to change routes. In the same way, if they perceived that their evacuation route was clear, they took 2.5 seconds to increase their speed to 1.8m / s. In the bottleneck areas, it was determined that people took a comfort distance of 0.9 meters.

All these variables were taken into account for the preparation of the evacuation simulation, both for scenarios without collapses and with collapses.

3.2. Structural behavior

3.2.1. General structural features. This paper analyzes a seven-story reinforced concrete building located in the city of Lima. The predominant system is structural walls, it is a regular system, it has no irregularity in plan or height. As the mass and weight has a total of 696,453 tons. and 6832.208 tonf. respectively. Likewise, the fundamental period of greatest translational is determined in the direction of analysis (x). where the major structural period approaches in 0.698 seconds.

3.2.2. Nonlinear static analysis. The development of the graph that relates basal effort versus superior displacement is presented. The result of one of the axes is shown in the following Figure 1, where in the elastic range the maximum displacement of the building is 17,588 mm when the basal effort is 2931.966 KN. No structural risk is recorded, so the building can be occupied immediately after a seismic event. In the inelastic range, the maximum displacement of the defined structure is 240.019 mm when the basal shear is 8635.636 KN.



Figure 1. Capacity curve xx direction.

3.2.3. Nonlinear Time history analysis. For response analysis over time, historical records are used. The forces, deformations and distortions are analyzed from the maximum values of the records used, in this case the earthquake of the year 1966, which is of greater magnitude, since it has a greater

impact on our analysis because it seeks structural failures in the simulation. As soon as the seismic record to be used, three historical cases have been scaled up with the “SeismoMatch” software, providing us with a new scaled record. These results are indicated in Table 1.

Table 1. Historical records.

Seism	Latitude	Length	Depth (km)	Magnitude (Mb)	Intensity
1966	-10.70	-78.70	24	8.1 Mw	VIII
1970	-9.36	-78.87	64	7.8 Mw	VIII
1974	-12.50	-77.98	13	6.6 Mb	VII

Therefore, after analyzing the structure, the lateral design displacements for each floor are obtained. Table 2 shows the values obtained for each floor of the building in the analysis direction (X). Where you can see that the highest value is 2,632 cm.

Table 2. Maximum displacement of the building-1966 seism.

Story	Load (Case/combo)	Desplac.Max (cm)
Floor 7	DIN X-X	2.632
Floor 6	DIN X-X	2.1677
Floor 5	DIN X-X	1.6903
Floor 4	DIN X-X	1.219
Floor 3	DIN X-X	0.7781
Floor 2	DIN X-X	0.4002
Floor 1	DIN X-X	0.1228

Evaluating the results of the plastic hinges, it can be seen that the formation of the hinges was occurring progressively, which indicates that the analysis performed well as shown in Figure 2a.

This behavior is demonstrated in the moment-curvature graph of the analyzed elements. Figure 2b shows the beam graph. The elements most affected by the earthquake entered were the walls and beams. The columns did not suffer much stress because the plates withstood 82% of shear forces, which justifies that the columns did not incur a mostly plastic range.

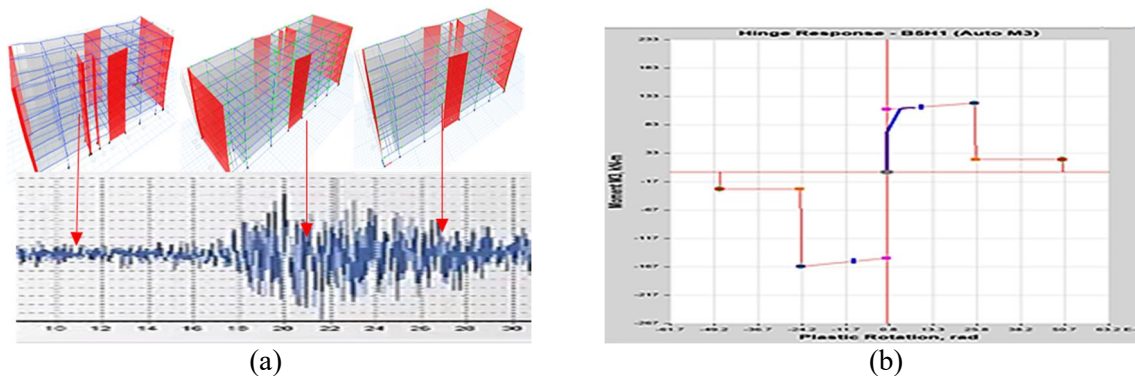


Figure 2. (a) Plastic hinge formation, 1966 seism. (b) Moment curvature graph of beam 34.

This structural behavior can be reflected in the modeling of buildings identifying the position and the moment in which the structural elements collapse. This type of processing of the results is essential to carry out the evacuation simulation later. Next, the collapsed structural elements, their place of collapse and instant of collapse are presented in Table 3.

Table 3. Collapsed structural elements.

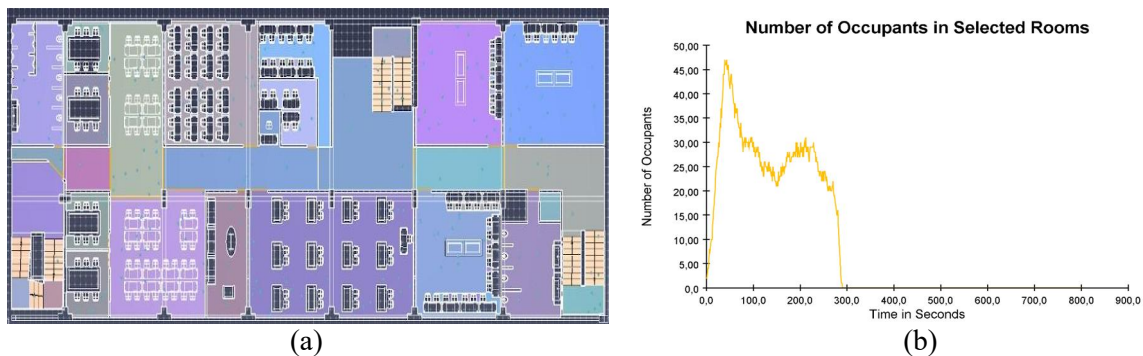
Collapse of structural elements					
Element	Location: Passage	Instant of collapse (Seconds)	Element	Location: Passage	Instant of collapse (Seconds)
Beam	Floor 1	28	Beam	Floor 4	28
Beam	Floor 2	27	Beam	Floor 5	28
Beam	Floor 2	24	Beam	Floor 5	30
Beam	Floor 2	24	Beam	Floor 6	33
Beam	Floor 3	26	Beam	Floor 6	33
Beam	Floor 3	26	Beam	Floor 7	33
Beam	Floor 4	29	Beam	Floor 7	33

3.3. Agent behavior without collapses

As indicated in the methodology section, evacuation simulations were performed for 3 scenarios. For the specific case of the educational institution, the most significant schedules were 7 AM, 12 PM and 7 PM. The simulations will be divided by simulation without collapses and collapses at the same period of time.

Referring to drills without collapses, these took an average evacuation time of 430 seconds, similar time as the recorded drill that took 420 seconds. People moved along evacuation routes in the same way as in the drill. Bottlenecks formed by people on the different evacuation routes were witnessed, specifically at the stairway entrances.

The control areas that were developed to simulate the collapse of structural elements, showed a large flow of people circulating. This is important because it is identified that these areas with high flow can be critical and important for the subsequent section of person-structure interaction. Figure 3a and 3b.

**Figure 3.** (a) Agent control zones. (b) graphical flow of people in room 23.

3.4. Interaction of behaviors

Collapses were obtained according to the plastic hinges of the nonlinear history time analysis. Only the hinges that marked impending collapse were taken into account to ensure that entrances to different areas are affected. With this information it was possible to extract the trapped people due to the collapses.

The zones carried out for this simulation are divided according to the route of the structural beams of the building. This procedure was carried out to take into account the collapse of beams and columns in all possible floors and places.

In addition to taking new evacuation routes, the collapse led to the formation of larger bottlenecks. It also created greater congestion of people in areas where there was free movement. It was determined that evacuation routes are not designed for this sudden increase of people. Figure 4a.

The collapse of continuous or parallel structural elements indicates that the area of involvement is large. This could be seen in the area where the agents were trapped during the evacuation without being able to leave by another route. This is the case of the 4th floor where it can be seen that the collapse of beams in parallel meant that 32 people were trapped without the possibility of evacuation. Figure 4b.

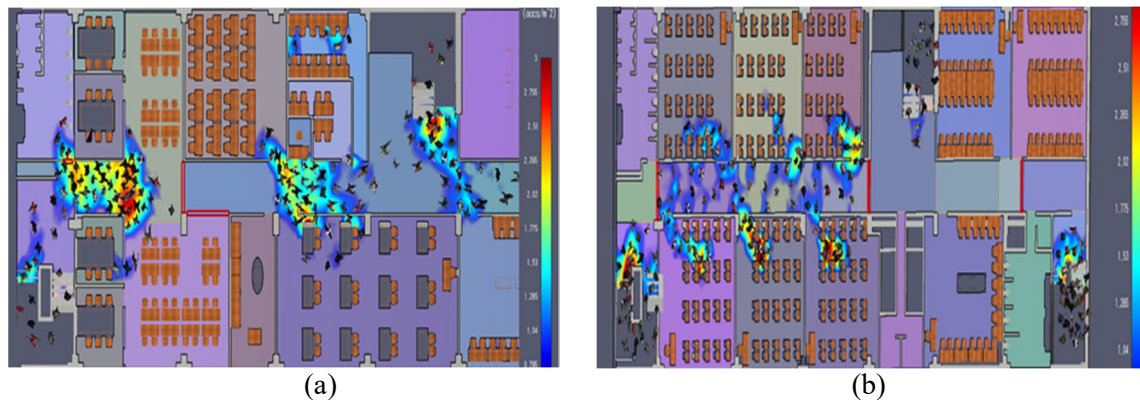


Figure 4. (a) Landslide evacuation route change. (b) People trapped floor 4.

Evacuation times were 560, 490, 520 seconds for the 7 AM, 12 PM and 7 PM schedules respectively. These took longer than in simulations without landslides, due to alternate route taking and increased accumulation of people on evacuation routes. A total of 65 agents were trapped along the evacuation routes on the different floors for the morning schedule, 43 for the midday and 55 for the evening.

4. Conclusions

The evaluation of essential buildings through the interaction of structural and human behavior provides a more complete analysis of important aspects, such as evacuation during emergencies, finding structural, architectural flaws and possible human affectations.

The structural damage of the building per floor is moderate due to the presence of collapsing beams. 94% of structural elements of the building did not enter a plastic state, remaining in an elastic behavior.

Evacuation routes were directly affected by the collapse of beams. According to the location of the collapsed beams, they traveled along the evacuation routes making it difficult to evacuate the simulated agents. This situation is critical considering that evacuation routes should be the least affected in the building.

100% of the floors of the building presented bottlenecks around the emergency exit entrances. The largest bottlenecks appeared on the stairs at the ends because there are access doors before it, causing a greater delay in the start of movement of people in them.

5% of the total simulated agents were trapped inside the building during the simulation. The areas with the highest number of trapped agents were in the central sector before the central stairs. The flow of people or agents was greater in that area due to the easy access of the central stairs. In addition, it evidences the structural deficit presented by the building in that area.

The interpolation of the duration of the earthquakes with the evacuation time of the agents shows an alarming situation. 95% of people to evacuate are still in the building even when the earthquake is over. The duration of the selected earthquakes is part of 17% of the total evacuation time both in the simulation and in the simulation. The structure experiences maximum stress during the first 100 seconds of evacuation, leaving the greatest number of people in the building in danger. The occurrence of collapses during this short time interval means people unable to evacuate to the point of being physically and psychologically damaged.

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