Research Article
Buildings, Causalities, and Injuries Innovative Fuzzy Damage Model during Earthquakes

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One of the human concerns has always been to estimate the damage caused before the earthquake and predict the extent of injuries and causalities. An effective model should be developed based on the field survey data for appropriate prediction. In this study, the degree of damage to the structure is first determined and the potential damage is then predicted using field data and fuzzy logic (FL). Effective parameters in the model include the structure height, building age, shear wave velocity in the soil, the plan equivalent moment of inertia, distance to the fault, earthquake factor, the number of inhabitants in the building, and the building height-to-width ratio (HWR). The parameters are fuzzily divided into five classifications: bad, relatively bad, medium, relatively good, and good. The model output parameter, which is the degree of damage to the building, is fuzzy and is divided into five classifications: complete damage, extensive damage, moderate damage, slight damage, and no damage. It should be noted that buildings with steel and concrete structures and moment frames, in the night, day, and traffic time scenarios, have very limited type 3 and 4 injuries with 32, 24, and 16 people, respectively, but type 1 and 2 injuries are significant. During the earthquake at night, the number of people with type 1 and 2 injuries is 975607 and 58757, in the event of the earthquake during the day, the number of people with type 1 and 2 injuries is 739096 and 44513, and during the earthquake at traffic time, the number of people with type 1 and 2 injuries is 492731 and 29675, respectively.

1. Introduction

One of the most important and destructive natural disasters is the earthquake that threatens the lives of many people in different parts of the world every year. There is a direct relationship between success in crisis management during an earthquake and the degree of hazard prediction. Predicting preearthquake damage leads to preparing for the consequences. The more the preparation and prediction are in line with the realities and the damage caused, the faster and safer the confrontation and rescue of the injured will be, and the less severe the injuries will be. Accordingly, the development of a model tailored to the realities of each region can provide more useful information to crisis managers and make any prediction or preparation for the crisis more realistic and effective. Planning for crisis management and assistance to the victims will be in line with the realities of a city and based on local and indigenous data and will facilitate the decision on necessary and preventive operations if a model can be developed to predict the degree of damage to the structure, other parameters affecting the quality of assistance before an earthquake in the city based on statistical data of the parameters affecting the damage to the structure, and also the factors affecting the rescue of
victims as quickly and efficiently as possible. In this case, the necessary operations can be planned more effectively and efficiently, and if necessary, retrofitting and optimal changes in the parameters affecting the damage can be done before the earthquake. Since Tehran is located in the area of severe earthquakes, its construction has special conditions, and, according to history, a very strong earthquake occurs every hundred years in this city, destroying a significant part of the city, an appropriate model should be developed to predict the degree of damage to the structure, financial loss, and casualties. This becomes doubly important when it has been a long time since the last earthquake, which caused significant damage to the city [1].

Due to the recurrence of high-intensity earthquakes, significant earthquakes can occur at any time, leading to human, financial, and economic catastrophe. This further clarifies the need for a comprehensive, field-based plan. Also in this study fuzzy model is utilized for precasting damage scenarios to control the damage to buildings and causalities and injuries during earthquakes [2]. Various methods have been proposed to analyze the constructed structures. Since buildings are constructed at different times and the quality of their design and construction is different, not only is the numerical analysis solution following all the parameters affecting the strength of a structure a practical way to achieve a good model of building behavior in a city, but also obtaining the numerical data necessary to analyze structures and investigate possible damage is a long, costly, and nonoperational task [3]. A method can be obtained to quickly and accurately develop a qualitative model for predicting the degree of damage to the structure based on field data in the city and plan a set of crisis management operations based on existing data using qualitative methods of examining structures and inferring effective parameters in a structure [4]. Municipalities can be informed of the extent of damage in a city before an earthquake occurs and take steps to reduce the damage caused by a potential earthquake through phase-out rehabilitation programs by developing an appropriate model. If municipalities know how many buildings in each area have how much possible damage to the structure and, consequently, possible financial and human losses, they can prioritize the reconstruction and retrofitting of those buildings that are most likely to be damaged and, if necessary, require the owners to perform retrofitting before any accident occurs [5]. Any precautionary measures in this regard cannot be compared with the future costs after the crisis, and the negative economic consequences of earthquakes are much greater than any retrofitting [6].

Numerous parameters affect the degree of damage to the structure, financial loss, causalities, and the severity of damage to the building. Many of these parameters depend on the local conditions of construction, the structure type and accuracy of construction, the building age and height, the geographical conditions of the structure in terms of soil type and distance to the fault, the population density of a city, and even access roads to provide assistance, etc. Crisp numerical and regional models cannot meet many of the qualitative parameters affecting this damage because including some of these parameters in numerical analysis based on crisp logic requires a very high time and cost and is infeasible. The results with acceptable accuracy can be achieved with low cost and high speed if a suitable qualitative model with good accuracy is proposed. Many relief organizations, such as the Red Crescent, the Disaster Management Organization, and other relief agencies, need data and models on the severity of damage to buildings, the performance of these buildings in critical conditions, and postcrisis access roads that are consistent with the realities of the city and region to prepare a specific plan in the event of a crisis such as an earthquake to plan and predict the severity of a city during the earthquake. Since a clear and codified plan for the relevant organizations will facilitate relief more effectively and quickly in the event of earthquakes, the importance of modeling in this regard will become more apparent [7].

2. Modeling Logic and Evaluation of Effective Parameters

Since this study is conducted to achieve a qualitative model for the severity of building damage and predict injuries after an earthquake based on field conditions and since the effective parameters in this modeling are qualitative, the model is developed based on fuzzy logic; as opposed to crisp logic, this logic, which is based on Aristotle’s value of zero and one, can be very useful, effective, and efficient in terms of parameters that are qualitative and not merely quantitative. Fuzzy logic is a method of examining linguistic and information uncertainties, and its qualitative conditions may not be properly considered if a fixed numerical value is assigned to it. Fuzzy logic can provide more realistic results than crisp logic in terms of qualitative analysis of some problems. The theory of fuzzy logic is based on the notion of relative graded membership, as inspired by the processes of human perception and cognition. Fuzzy logic is extremely useful for many people involved in research and development including engineers (electrical, mechanical, civil, chemical, aerospace, agricultural, biomedical, computer, environmental, geological, industrial, and mechatronics), mathematicians, computer software developers and researchers, natural scientists (biology, chemistry, Earth science, and physics), medical researchers, social scientists (economics, management, political science, and psychology), public policy analysts, business analysts, and jurists. Indeed, the applications of fuzzy logic, once thought to be an obscure mathematical curiosity, can be found in many engineering and scientific works [8].

The fuzzy logic and classification methods provided in this model can present each of the effective parameters in the modeling as an acceptable expression set and determine the boundary limits of the classification using the field study. It is possible to classify and present the classification range of the parameters using the fuzzy c-mean (FCM) method [9]. In this study, the supervised center classification method is used to cluster and determine the membership function range of input and output parameters [10]. This is a realistic method with less error because the classification is based on
data from field surveys. The parameters considered in this study are as follows for moment frames of steel structures as well as concrete structures separately and are obtained based on field surveys in the city [11]. It derives the global building damage level from that reported information by trained technical staff, after in situ visual inspection of the main parameters, i.e., the "structural components" and the "nonstructural components". These parameters describe the relationship between the components’ damage and the global damage level of the building. For this purpose, it is required that fuzzy sets and their membership functions should be adequately identified [12].

One of the most important factors in assessing the damage to a building is the presence or absence of an earthquake code during the construction of the structure. Since the first edition of the Iranian Code of Practice for Seismic Resistant Design of Buildings came into force in 1987, buildings before this date did not have any calculations concerning the seismic forces. So, the examination of these buildings should be done accordingly. Subsequent editions of the Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800) in 1999, 2005, and 2014, entitled Second to Fourth Editions, became the criterion for action. So, according to the above, the building age and the seismic design classification of each building should be taken in the field survey to be considered during the relevant calculations. Since the acceleration applied to the structure during an earthquake depends on the parameters of basic design acceleration, natural period, reflection coefficient, importance factor, and behavior factor, the amount of acceleration applied to the structure should be determined by taking and calculating each of the above parameters [5, 13].

One of the factors affecting the torsional stiffness of the structure during an earthquake is the equivalent moment of inertia of each floor. In this study, the moment of inertia around the weak axis of each floor is considered as the equivalent moment of inertia of the building and as a measure of lateral and torsional stiffness in the structure in the fuzzy model [14].

Another factor affecting the amount of seismic force applied to each building is the shear wave velocity in the soil and the soil type. The soil of each building is divided into four different types I, II, III, and IV according to the average shear wave velocity, the number of standard penetration tests (SPTs), and the average undrained shear strength in sticky soils. The shear wave velocity is included in the calculations according to the Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800). Among the factors affecting the calculation of seismic lateral loads are the natural period of the building and the ductility and damping of the structure. These factors are commensurate with the number of floors in a building. The number of floors and the height of the constructed buildings should be taken separately during the field survey to be taken into account when modeling and calculating the degree of damage to the structure and human losses [15].

One of the factors affecting the amount of force applied to a structure during an earthquake is the distance between the building in question and the fault activated in that earthquake. The shorter the distance, the greater the force applied to the structure and, consequently, the greater the damage. So, this distance is considered one of the effective input parameters in the model. One of the most important factors preventing easy assistance to the damaged buildings and rescuing the victims after the earthquake is the lack of access to those places due to the debris caused by the destruction of buildings on the access roads. The most important aggravating factor is the width of the passage. The smaller the width of the passage and the higher the height of the buildings constructed in that passage, the more likely it is that the passage will be blocked and, consequently, the problems of access of rescue teams to the injured will increase. Therefore, the parameter of the building height-to-width ratio (HWR) is one of the input parameters of the model. The number of injuries and deaths in each building during an earthquake is directly proportional to the number of inhabitants in the building. Therefore, the number of inhabitants and units of each building should be specified in the field survey so that the data obtained are suitable and reliable representatives in modeling studies [3].

3. Field Survey and Data Analysis

Since the method used in this study is based on field statistical data, the effective parameters in modeling are collected from 527 buildings in the city. Attempts have been made to collect data from all areas of the city so that the model is more appropriate for all areas. Data on the building age, structure height, type, length, and width, the width of the passage, and the number of inhabitants in the building are collected by visiting the building, by asking inhabitants, and through structural drawings. Data on soil type are taken from the soil type zoning map of the Center for Geotechnical Studies and Material Strength of Tehran Municipality. In the field survey, the distance between the building and the existing faults is calculated according to the seismic history of the seismic source [16]. The criterion for calculating this distance is the Tehran fault map prepared by the International Institute of Earthquake Engineering and Seismology (Table 1).

4. Parts of the Fuzzy Model in the Study

Each fuzzy model consists of three completely separate parts. The first part includes input parameters, the second part includes fuzzy inference or fuzzy rules database, and the last part includes output parameters. Input parameters include the structure height, building age, shear wave velocity in the soil, the plan equivalent moment of inertia, distance to the fault, earthquake factor, the number of inhabitants in the building, and the building height-to-width ratio (HWR). The middle part of the fuzzy model is the inference part, in which the rules of the model are expressed based on propositions that are as if, then. The last part is the model output and displays the degree of damage to the building. Figure 1 shows these parts [17]. The membership functions of the input and output parameters are used to display the parameters of the Mamdani fuzzy model. The membership functions used in this study are five membership functions whose range is

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obtained based on statistical data obtained from field surveys as described in the supervised center classification or the FCM method. In this method, the input parameters are divided into five classifications: bad (B), relatively bad (RB), moderate (M), relatively good (RG), and good (G), and the ranges of these five classifications are obtained according to the supervised center classification method (SCC-FCM) [6, 12]. Furthermore, the output parameter of the model, which is the degree of damage to the building, is divided into five classifications, including no damage (ND), slight damage (SD), moderate damage (MD), extensive damage (ED), and complete damage (CD). The membership function range of this fuzzy parameter is determined based on the above method and the data obtained from the field survey [5, 13].

5. Membership Functions of Input and Output Parameters Based on Field Survey

The following rules are used to determine the membership function range of input parameters by the SCC-FCM method [18]. The minimum values obtained from the field survey are the range G in the parameters whose lower values are more desirable and the range B in the parameters whose higher values are more desirable [19]. For example, the building age is a parameter whose lower values are more desirable, while the greater the distance to the fault, the more desirable it is.

The maximum values obtained from the field study are range B in the parameters whose lower values are more desirable and range G in the parameters whose higher values are more desirable. The mean values obtained from the field survey are in the range M either when lower parameters are more desirable or when higher parameters are more desirable. The mean minimum values obtained from the field survey are the RG range in the parameters whose lower values are more desirable and the RB range in the parameters whose higher values are more desirable. The mean maximum values obtained from the field survey are the RB range in the parameters whose lower values are more desirable and the RG range in the parameters whose higher values are more desirable (Figure 2).

According to these rules, Tables 2 and 3 are obtained in steel and concrete structures, which are the criteria for the membership function range in the model input parameters, the example of which can be seen in Figure 3.

The distance between the degrees of damage to the building should be calculated using equation (1) and the cumulative sum of the distances should be obtained to determine the membership function of the output parameter based on the field survey and the SCC-FCM method. This cumulative distance is the degree of damage to the building, and its quality range is the degree of hazard [9].

\[
d_{ik} = d(x_k - v_i) = \left[ \sum_{j=1}^{m} (x_{kj} - v_{ij})^2 \right]^{1/2}
\]  

(1)

The membership function of the output parameter in steel and concrete structures is obtained according to

![Flowchart of the fuzzy model sections and subsections.](image1)

![An example of a building height membership function as an input parameter.](image2)
### Table 1: Samples of field survey of concrete structures.

| Row | Block number | Building number | Structure type | Building age (years) | Length (m) | Width (m) | Structure height (m) | Passage width (m) | The number of inhabitants (persons) | Soil type | Shear wave velocity in soil (m/s) | Distance to the fault (m) | Height-to-width ratio (HWR) | Moment of inertia around the weak axis (m$^4$) | Earthquake factor |
|-----|---------------|-----------------|----------------|---------------------|------------|----------|--------------------|-------------------|-------------------------------------|------------|-------------------------------|------------------|-----------------------------|-----------------------------------|------------------------|
| 1   | 60781         | 4               | Steel          | 20                  | 20         | 10       | 12                 | 16                | 24                                  | 2          | 560.00                        | 850               | 0.750                        | 1,667                          | 0.170                  |
| 2   | 60781         | 6               | Steel          | 15                  | 20         | 10       | 24                 | 16                | 40                                  | 2          | 560.00                        | 900               | 1.500                        | 1,667                          | 0.108                  |
| 3   | 37515         | 13              | Steel          | 13                  | 31.4       | 9.6      | 19                 | 12                | 44                                  | 2          | 560.00                        | 900               | 1.583                        | 2,315                          | 0.126                  |
| 4   | 37515         | 12              | Steel          | 11                  | 31.4       | 9.6      | 20                 | 12                | 40                                  | 2          | 560.00                        | 950               | 1.667                        | 2,315                          | 0.122                  |
| 5   | 37516         | 15              | Steel          | 10                  | 33.95      | 12.5     | 10                 | 12                | 16                                  | 2          | 560.00                        | 1200              | 0.833                        | 5,526                          | 0.175                  |
| 6   | 37515         | 2               | Steel          | 25                  | 26         | 12       | 6                  | 12                | 40                                  | 2          | 560.00                        | 1250              | 0.500                        | 3,744                          | 0.175                  |
| 7   | 37516         | 17              | Steel          | 14                  | 22         | 10       | 21                 | 12                | 24                                  | 2          | 560.00                        | 1200              | 2.000                        | 1,833                          | 0.118                  |
| 8   | 37516         | 18              | Steel          | 5                   | 22         | 10       | 24                 | 12                | 24                                  | 2          | 560.00                        | 1200              | 0.833                        | 2,000                          | 0.108                  |
| 9   | 37494         | 7               | Steel          | 15                  | 25.7       | 15       | 15                 | 12                | 32                                  | 2          | 560.00                        | 1000              | 1.250                        | 7,228                           | 0.147                  |
| 10  | 37476         | 20              | Steel          | 40                  | 35.6       | 15.5     | 6                  | 12                | 8                                   | 2          | 560.00                        | 1200              | 0.500                        | 11,047                         | 0.175                  |
| 11  | 37463         | 8               | Steel          | 20                  | 37.7       | 22.6     | 6                  | 12                | 12                                  | 2          | 560.00                        | 800               | 0.500                        | 36,265                         | 0.175                  |
| 12  | 37377         | 36              | Steel          | 14                  | 24         | 12.5     | 20                 | 12                | 32                                  | 2          | 560.00                        | 1020              | 1.667                        | 3,906                          | 0.122                  |
| 13  | 30021         | 6               | Steel          | 20                  | 16.4       | 13       | 20                 | 10                | 12                                  | 3          | 275.00                        | 4100              | 2.000                        | 3,003                          | 0.180                  |
| 14  | 29419         | 9               | Steel          | 25                  | 16.4       | 8        | 9                  | 10                | 12                                  | 3          | 275.00                        | 4200              | 0.900                        | 700                            | 0.193                  |
| 15  | 29417         | 2               | Steel          | 5                   | 20.3       | 7        | 12                 | 10                | 12                                  | 3          | 275.00                        | 4200              | 1.200                        | 580                            | 0.193                  |
| 16  | 29407         | 1               | Steel          | 20                  | 25.2       | 23.3     | 18                 | 24                | 80                                  | 3          | 275.00                        | 4200              | 0.750                        | 26,564                         | 0.193                  |
| 17  | 49185         | 3               | Steel          | 25                  | 15.85      | 12       | 6                  | 20                | 16                                  | 2          | 560.00                        | 900               | 2.000                        | 8,296                           | 0.175                  |
| 18  | 49186         | 2               | Steel          | 45                  | 12.8       | 12.2     | 6                  | 10                | 6                                   | 2          | 560.00                        | 1200              | 2.033                        | 7,864                          | 0.175                  |
| 19  | 49624         | 2               | Steel          | 25                  | 23         | 21.15    | 12                 | 15                | 24                                  | 2          | 560.00                        | 1950              | 1.763                        | 25,348                         | 0.170                  |
| 20  | 49624         | 9               | Steel          | 35                  | 26         | 9.5      | 8                  | 15                | 12                                  | 2          | 560.00                        | 1950              | 1.188                        | 51,263                         | 0.175                  |
Figures 4 and 5 by calculating the distances of the degree of damage in the output parameters in steel and concrete structures and according to the values obtained in Table 4.

6. Fuzzy Model Rules, Computer Modeling, and Results

The rules of the fuzzy model are a set of relations that are as if, then, establishing the relationships between the input and output parameters. The necessary inference is made and the desired results are obtained using these rules. There are many sets of rules between input and output parameters. However, not all of these rules are valid. Since there are 8 input parameters with five classifications of membership functions in this study, the number of possible rules is equal to 5 to the power of 8. In other words, the total number of possible rules is equal to 390,625, but not all of these rules are valid. Studies typically use a small number of rules, a maximum of a few dozen valid rules. In this study, 92 rules are used for the fuzzy model based on the following principles:

(1) The output parameter classification will be as complete damage (CD) if all values of the input membership functions are simultaneously B.

(2) The output parameter classification will be as no damage (ND) if all values of the input membership functions are simultaneously G.

(3) The output parameter classification will be as moderate damage (MD) if all values of the input membership functions are simultaneously M.

(4) The output parameter classification will be as extensive damage (ED) if all values of the input membership functions are not B, G, or M and are in the range RB.

(5) The output parameter classification will be as slight damage (SD) if all values of the input membership functions are not B, G, or M and are in the range RB.

Table 2: The input membership function range of steel structures.

| Steel structure | The building age | Shear wave velocity in soil | Structure height | Earthquake factor | The number of inhabitants | The moment of inertia around the weak axis | Distance to the fault | The building height-to-width ratio (HWR) |
|-----------------|-----------------|-----------------------------|-----------------|------------------|--------------------------|------------------------------------------|---------------------|----------------------------------------|
| G               | 1.0             | 560.00                      | 3.00            | 0.0599           | 4                        | 425600                                   | 8200                | 0.20                                   |
| RG              | 11.0            | 509.55                      | 9.61            | 0.1088           | 19                       | 222002                                   | 5312                | 0.74                                   |
| M               | 21.1            | 459.11                      | 16.21           | 0.1577           | 34                       | 18405                                    | 2424                | 1.28                                   |
| RB              | 40.5            | 367.05                      | 41.22           | 0.1751           | 143                      | 9265                                     | 1312                | 3.40                                   |
| B               | 60.0            | 275.00                      | 66.23           | 0.1925           | 252                      | 125                                       | 200                 | 5.52                                   |

Table 3: The input membership function range of concrete structures.

| Concrete structure | The building age | Shear wave velocity in soil | Structure height | Earthquake factor | The number of inhabitants | The moment of inertia around the weak axis | Distance to the fault | The building height-to-width ratio (HWR) |
|--------------------|------------------|-----------------------------|-----------------|------------------|--------------------------|------------------------------------------|---------------------|----------------------------------------|
| G                  | 1.0              | 560.00                      | 6.00            | 0.0693           | 6                        | 674371                                   | 6200                | 0.30                                   |
| RG                 | 5.9              | 512.87                      | 12.59           | 0.1088           | 25                       | 354597                                   | 4194                | 1.07                                   |
| M                  | 10.8             | 465.75                      | 19.17           | 0.1482           | 44                       | 34823                                    | 2188                | 1.84                                   |
| RB                 | 30.4             | 370.37                      | 31.79           | 0.1704           | 214                      | 17470                                    | 1194                | 3.92                                   |
| B                  | 50.0             | 275.00                      | 44.40           | 0.1925           | 384                      | 117                                       | 200                 | 6.00                                   |

Figure 3: The membership function of the degree of damage to steel structures.

Figure 4: The membership function of the degree of damage to concrete structures.
(6) The output parameter classification will be as no damage (ND) if all values of the input membership functions are G and only one parameter is not G.

(7) The output parameter classification will be as slight damage (SD) if all values of the input membership functions are RG and only one parameter is not G.

Figure 5: A fuzzy model for predicting the degree of damage to a building after an earthquake.
(8) The output parameter classification will be as moderate damage (MD) if all values of the input membership functions are M and only one parameter is not M.

(9) The output parameter classification will be as extensive damage (ED) if all values of the input membership functions are RB and only one parameter is not RB.

(10) The output parameter classification will be as complete damage (CD) if all values of the input membership functions are B and only one parameter is not B.

The fuzzy model is implemented using MATLAB software. In this model, a fuzzy model is obtained in MATLAB software by specifying the membership functions of the eight input parameters and the membership function of the degree of damage as the output parameter, as well as the model rules so that the degree of damage to any other building can be predicted based on the qualitative model and field data obtained by specifying the input parameters including the structure height, building age, shear wave velocity in the soil, the plan equivalent moment of inertia, distance to the fault, earthquake factor, the number of inhabitants in the building, and the building height-to-width ratio (HWR). Figure 5 shows part of the 92 rules used in the model as an example, representing the contribution of input parameters as a result of the model with the Mamdani method and the centroid defuzzification method. The model allows the degree of damage to the new structure to be calculated by changing each of the input parameters of the degree of damage to the structure depending on the nature of the input parameter and the fuzzy model rules. As can be seen in Figure 5, the characteristics of a concrete building such as an age of 25 years, $pgv = 425$, a height of 25 m, $C = 0.125$, 200 inhabitants, the moment of inertia $I = 4e + 05$, distance to the fault of 3500 m, and the height-to-width ratio (HWR) of 3.5 are given as input parameters to the model, and a degree of damage of 0.774 is obtained as the output parameter. This model provides the possibility to predict the degree of damage to the structure before the earthquake by entering eight input parameters. By obtaining the degree of damage, the percentage of probability of damage to one of the fuzzy concepts of damage to the structure, including five classifications of no damage (ND), slight damage (SD), moderate damage (MD), extensive damage (ED), and complete damage (CD), is obtained to predict damage to each building against future earthquakes.

Besides, the behavior of the model can be changed by changing input parameters. Several curves of changes in input parameters and the degree of damage to the structure can be seen in the total dash 6. This figure shows the changes in the building age and the degree of damage. According to the figure, it is found that changes in the degree of damage are upward in buildings with a short life of up to about 8 years, remain unchanged in the age of 8 to 18 years, and again increase with a low slope in the age of more than 18 to 50 years. Moreover, buildings aged 8 to 18 years behave the same in the degree of damage to them, assuming that other effective parameters are constant. Figure 6 also shows the changes in the equivalent moment of inertia of the building with the degree of damage to the structure. As can be seen in this figure, buildings behave the same in moments of inertia of 50,000 to 400,000 m$^4$, but the extent of damage to the building is greatly reduced from moments of inertia of more than 400,000 m$^4$. Figure 6 also shows the changes in structure height with the degree of damage to the structure. As can be seen in this figure, buildings behave the same and show the same damage, but the degree of damage to the structure increases under the same conditions in terms of other parameters from a height of 28 meters and above. According to Figure 6, the distance between buildings and faults can be classified into three categories. If the distance to the fault is less than 1500 meters provided that other parameters are constant, the degree of damage will increase. If the distance is between 1500 and 4800 meters, there is not much change in the degree of damage to the structure, and at distances of more than 4800 meters, the degree of damage is reduced provided that other parameters are constant.

### 7. Estimation of Causalities and Injuries Caused by Earthquakes Using the Proposed Model

According to the FEMA method proposed for predicting casualties and injuries caused by earthquakes, four types of injuries may occur in the event of an accident such as an earthquake [20]. Type 1 injuries (minor injuries): These
types of injuries, such as suture-requiring incisions (grades 1 and 2 in small parts of the body), head trauma without loss of consciousness, low burns, and low twists and fractures, can be treated with first aid by professionals. Type 2 injuries (injuries requiring hospitalization): These types of injuries, such as second- and third-degree burns to a large part of the body, head trauma that causes unconsciousness, significant fractures, and dehydration, require imaging or surgery but are not life-threatening. Type 3 injuries (life-threatening injuries): These types of injuries, such as uncontrolled bleeding, internal injuries, and spinal cord injuries, are life-threatening. Type 4 injuries (death): These include rapid death or fatal injuries.

Three earthquake scenarios are considered to examine the extent of each of the above types of injuries.

Scenario 1: The night scenario in which an earthquake is assumed to occur at 2 a.m.

Scenario 2: The day scenario in which an earthquake is assumed to occur at 2 p.m.

Scenario 3: The traffic time scenario in which an earthquake is assumed to occur at 5 p.m.

In each of the above scenarios, the above four injuries inside and outside the building can be examined separately. Since the purpose of this study is to investigate the casualties and injuries occurring inside the building, only indoor casualties and injuries are investigated, and no casualties or injuries occurring outside the building in open areas and access roads are investigated. Since this study only examines residential buildings, inhabitant coefficients of 0.99 (the number of inhabitants in the desired building relative to total inhabitants) for 2 a.m., 0.7 for 2 p.m., and 0.5 for the 5 p.m. are extracted and used according to the proposed FEMA method. According to the field survey, the number of inhabitants of 527 buildings understudy is 20,690. The number of each of the above injuries is listed in Table 5. If this model is generalized to Tehran, in the scenario of an earthquake at 2 p.m., at least 739,096 people will suffer from type 1 injuries, 44,513 people from type 2 injuries, 24 people...
from type 3 injuries, and 24 people from type 4 injuries. For the 2 a.m. scenario, these numbers are 975607, 59350, 32, and 32, respectively, and for the 5 p.m. scenario, 492731, 29675, 16, and 16, respectively.

8. Conclusion

Injuries are classified into four classifications of injuries 1 to 4. In this study, the range of membership functions of input and output parameters is determined using the supervised hazard center classification method. The obtained fuzzy model leads to a qualitative determination of the degree of damage to the structure and prediction of damage and injuries based on field surveys. Assessing city buildings in the event of future earthquakes and determining the extent of damage to a building is always very important from the point of view of rescue planning for the victims as well as urban resilience programs that reduce future human and economic losses. To achieve this goal, either classical models and numerical methods with various hypotheses should be used with considerable time and cost, or qualitative methods based on field studies and fuzzy logic with less time should be used and with the linguistic expression of uncertainties. In this study, a fuzzy model is developed using field survey and conventional methods to determine the range of membership functions of linguistic data uncertainties so that the degree of damage can be classified into five categories including complete damage (CD), extensive damage (ED), moderate damage (MD), slight damage (SD), and no damage (ND) in any building whose input parameters are known. Investigation of model outputs and behavior in changes of input parameters such as the building age, structure height, distance to the fault, plan equivalent moment of inertia, etc. suggests that the degree of damage in changing each of these parameters and increasing and decreasing each is very sensitive and that, with the change of each input parameter, the degree of damage to the building against the earthquake is associated with significant changes.

Preliminary results lead to the development of a fuzzy model that can be used to calculate the degree of damage to the structure so that the structure height, building age, distance to the fault, and other input parameters can be entered in this model and its output can be the degree of damage to the structure in each structure. The percentage of damage probability in each of the five categories of complete damage, extensive damage, moderate damage, slight damage, and no damage can be calculated by calculating the degree of damage to the structure and applying it to the membership function of the output parameter. By changing the input parameters in other buildings, the degree of damage to the structure and the probability of damage in the five categories for the building will be obtained, and this is a good model for predicting the degree of damage to a building during an earthquake based on data obtained by field survey. After predicting the degree of damage to buildings with concrete and steel moment frames in Tehran, the number of casualties and injuries of this type of buildings during the earthquake is estimated and the number of four types of injuries reported in FEMA is calculated separately.

Data Availability

The data used to support the findings of the study can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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