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Evaluation of Earthquake Performance of Reinforced Concrete Buildings with Fuzzy Logic Method

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Abstract
A reinforced concrete building is a type of building whose structural system consists of reinforced concrete columns, beams, shear walls, slabs, and foundations. It has been observed that reinforced concrete buildings have been severely damaged or collapsed even in moderate shaking. Evaluating buildings after earthquakes and their performances are quite important for the safety of life and property. In the literature, different methods have been developed for pre-earthquake evaluation of buildings, either low-cost and rapid or slow and high-cost and tool-demanding. In this study, in order to overcome the gap in the literature, the evaluation of the earthquake performance of buildings with the fuzzy logic method is discussed. In this context, the buildings' performance was evaluated by considering the concrete compressive strength, number of stories, ground floor area, area of column and shear walls, and architectural parameters. The data of 18, 28, and 146 buildings affected by the earthquakes in Afyon, Bingöl, and Van provinces in 2002, 2003, and 2011, respectively, were used in the study. Out of the 192 building data, 94 buildings were processed as data, and fuzzy logic rules available in Matlab were applied. The remaining 98 buildings were tested with this method. The buildings considered are light, moderate, and severely damaged or collapsed. The proposed method can be classified as rapid tier two (or level two) evaluation. According to the results, an 88% success rate was achieved which indicates the importance of the fuzzy logic method that can be utilized in determining the seismic performance of reinforced concrete buildings.

1. Introduction

Due to earthquakes, many lives have been lost in Türkiye until today. Damages to buildings also have caused great economic losses. Table 1 shows the significant earthquakes in Türkiye that occurred between 1990 and 2023 whose moment magnitude was greater than 6. The quick and reliable identification of the seismic performance of buildings before an earthquake gains importance after every earthquake. In particular, the February 6, 2023, Kahramanmaraş-Pazarcık (Mw=7.7) and Elbistan (Mw=7.6) earthquakes damaged many types of structures in 11 provinces. Rapid seismic performance assessment methods were also needed after these earthquakes [1, 2].

In recent years, studies on the earthquake performance of reinforced concrete buildings have increased in earthquake-prone countries. Considering that hundreds of buildings are damaged after earthquakes and pose a high risk, it becomes impossible to conduct detailed research because of its high cost and the great time it needs. In these methods, the final performance is obtained after performing linear or nonlinear analysis which needs geometric properties of the buildings and material tests of each

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building [3]. Therefore, a long time and high cost are required for the implementation of detailed methods. Due to time and cost constraints, rapid evaluation methods have been developed. Those methods try to reach consistent results in a short time and at a low cost with simple analyses using less data. Although rapid assessment methods provide a lot of information about the building, they do not qualify as a final decision [4-6].

In the literature, for pre-earthquake damage assessments, 3-stage assessment (namely first, second, and third level) methods have been established requiring low to high amounts of data. The first level is called rapid visual screening, in which a building's seismic performance is to be determined by considering visual properties from outside and simple calculations without using the project or material data. In this method, geometric properties and material tests are not required. A score calculation is made with certain parameters and a risk score is given to the building. The main purpose here is to quickly group buildings according to their risk status. FEMA 154 (2002), ATC 21, Regulation on Determination of Risky Buildings (RYTEİE-2019), and Sucuoglu and Yazgan (2003) are examples of first-level assessment methods [7-10].

In the second level evaluation methods, unlike the first level, additional data such as the geometric properties of the building, size and location of structural elements, material properties, and architectural parameters may be used. This method aims to determine the risk status of the building quickly and with simple calculations. Methods proposed by Hassan and Sozen (1997), FEMA310 (1998), Otani (2000), Japan Building Disaster Prevention Association (JBDPA) (2001), Ozcebe et. al. (2003), Sucuoğlu and Yazgan (2003), Yakut (2004), Boduroğlu et. al. (2004, 2007), Temur (2006), Tezcan et. al. (2011), İlki et. al. (2014), Sucuoğlu et. al. (2015), ASCE 41-17 (2017), Kaplan et. al. (2018) Erdil and Ceylan (2019) are examples of second level assessment methods [3, 10-24].

The analysis of the structures with the help of programs developed according to the principles of the relevant regulations is handled in the third-level evaluation methods. At this stage, more detailed work is carried out. Many parameters such as material properties of the building, damaged elements, size and location of the structural elements, and information regarding the reinforcements are taken into consideration. Linear and nonlinear methods given in the Turkish Building Earthquake Code -2018 (TBEC-2018), can be given as an example for the third-level evaluation [25].

This study aims to evaluate the seismic performance of reinforced concrete buildings using the fuzzy logic method with a certain number of data to be an alternative method in second-level assessment. The fuzzy logic method and its place in civil engineering are mentioned under the title of material and method. Data from 146 buildings affected by the earthquakes that occurred in Van on October 23 and November 9, 2011, 18 buildings affected by the 2002 Afyon earthquake, and 28 buildings affected by the 2003 Bingöl earthquake were used in the study [3].

Table 1. Major earthquakes with a magnitude greater than 6 that occurred between 1990 and 2023 [26-28]

Earthquake Location	Date	Magnitude	Human Loss	Number of Damaged Buildings	Economic Loss, TL
Erzincan	13.03.1992	6.6	653	8057	750.000
Ceyhan (Adana)	28.06.1998	6.2	146	31463	550.000
Gölcük (Kocaeli)	17.08.1999	7.6	17480	73342	20.000.000
Düzce-Bolu	12.11.1999	7.2	763	35519	1.000.000
Çay-Sultandağı/ Bolvadin (Afyon)	03.02.2002	6.5	44	622	95.000
Merkez (Bingöl)	01.05.2003	6.4	176	6000	135.000
Merkez (Van)	23.10.2011	6.7	644	17005	1.500.000
Sivrice (Elâzığ)	24.01.2020	6.8	41	1815	
Ege Denizi (İzmir)	20.10.2020	6.6	117	475	
Pazarcık (Kahramanmaraş) Elbistan (Kahramanmaraş)	06.02.2023 07.02.2023	7.7 7.6	50783	260000	104.000.000.000

2. Material and Method

2.1. Fuzzy Logic Method and Its Use in Civil Engineering

The concept of Fuzzy Logic was introduced by Lotfi A. Zadeh in 1965 [29]. However, the first application was realized by Mamdani in 1973 [30]. Mamdani used this method to balance the steam pressure of a steam engine. In addition, Mamdani stated that the fuzzy logic approach that Zadeh created with linguistic rules can be easily processed in a computer environment [31]. Until today, the fuzzy logic method has shown quick development and has been used in many fields such as health, economy, education, and engineering. The concept of fuzzy logic can be perceived as the modeling of the ability to think, learn, and reason with this information that people perform in normal life in a computer environment. For the processing of this modeling, information can be given verbally, but the computer can process verbal data with numerical values and draw new conclusions [32]. The contribution of fuzzy logic to rapidly developing artificial intelligence studies and control systems is quite high. Studies in this field are progressing with fuzzy logic [33]. In the classical logic of mathematics, a proposition is either true or false. If a proposition is true, it is expressed numerically with 1, and if it is false with 0. However, in daily life, situations or events may not occur with precise information and uncertainties may arise between 1 and 0 [34]. Fuzzy logic comes into play at the point of uncertainty. According to Zadeh [22], an element in a fuzzy set can take a value between 1 and 0. The closer the membership degree of an element is to 1, the more it belongs to the set, and it is accepted that the degree of belonging increases. In addition, unlike classical logic, something can be both true and false in fuzzy logic. This varies according to the condition to which it is connected. In other words, for nested propositions, the truth of the proposition may change as the condition changes.

The fuzzy logic method has been used in many applications in civil engineering. Chao and Cheng (1998) [35] tried to determine crack control in reinforced concrete elements with a fuzzy pattern model. In the study, logical inference was made by considering time, depth, regularity, spacing, pattern, and location parameters for the crack. As a result, it is reported that a problem that is difficult to solve with mathematical solutions can be understood in a simple way. Aldawod et al. (2001) [36] investigated the behavior of a 306 m high, 76-floor building in Melbourne, Australia, under wind using the fuzzy logic method. In this building, a damping system was created with a special mass. The fuzzy logic method was used to control the damper and the building. According to the results obtained, it is stated that the fuzzy logic method gives more consistent results than the classical logic method. Kömür (2004) [37] investigated post-earthquake damage detection and earthquake safety of buildings with the fuzzy logic method. Relative floor drifts and concrete characteristic compressive strength was used in fuzzy logic for post-earthquake damage assessment. As a result, it was stated that more consistent and realistic results were found compared to classical logic. In Lin et al. (2004) [38], the early strength of concrete was evaluated according to fuzzy logic. Cement, water, and aggregate variables were processed in fuzzy logic. The results were compared with regression analysis, and it was stated that the results were acceptable. Tanyıldızı and Yazıcıoğlu (2006) [39] tried to determine the plastic collapse load value of steel beams using the fuzzy logic method. The collapse load value for the plastic moment generated in the steel beam was solved with fuzzy logic. In the study, for two beams, the fuzzy logic was used to input load and distance information and output rotation data. While the rule base is expert experience, the membership functions are selected according to the experience gained. Base values were found by trying many changes. As a result, it is stated that the fuzzy logic method gives consistent results. In Çakıroğlu et al. (2010) [40], the 7, 14, and 28-day compressive strength of concrete was predicted by fuzzy logic. For this purpose, 7, 14, and 28-day compressive tests of 9 standard cylinder and cube specimens were performed. The test results were processed with fuzzy logic and the results were compared. It was concluded that the fuzzy logic results were quite close and within acceptable limits. Doran et al. (2015) [41] investigated the structural behavior of FRP (Fiber Reinforced Polymer) reinforced columns using fuzzy logic. In the study, column width, length, compressive strength, thickness, and modulus of elasticity of FRP are input parameters while one output parameter is taken as output. According to the results, the structural behavior of FRP-reinforced columns was predicted and reliable results were found. Prieto et al. (2017) [42] tried to predict the service life of historical buildings with the fuzzy logic method. In the fuzzy logic method, vulnerabilities and risk variables that affect the performance of buildings are taken into account. In the study, five historical buildings in Spain were taken into consideration. In the study, building management and maintenance processes were taken as input parameters while service life was taken as output. As a result, it is stated that the fuzzy logic method can be used in determining the service life of buildings.

2.2. Material

2.2.1. General features of the investigated buildings

In the study, data from 18, 28, and 146 buildings affected by the earthquakes in Afyon, Bingöl, and Van provinces in 2002, 2003, and 2011, respectively, were used. A total of 94 out of 192 buildings data were utilized for training in Matlab.

Details of the properties of the buildings were given in Erdil and Ceylan (2019) [3]. The number of lights, moderate and severely damaged buildings are 81, 17 and 58, respectively. The remaining 36 buildings were collapsed. In Erdil and Ceylan (2019), a number of stories, concrete compressive strength, ground floor area, and the ratio of the total vertical load-carrying member to the total floor area are stated to be the more important parameters that relate to the seismic performance of a building. Since similar parameters were mentioned in different studies [10, 11, 15-22, 43-45] parameters given in [3] were considered to be used directly in this study.

A number of stories is found to be more effective on the damage level. The damage level was found to increase with the increase in the number of stories [3, 10, 20, 21]. It is also observed that the mass of the building increases with the increase in the number of floors and the damage in the buildings with low earthquake resistance increases. It was stated that the percentage of moderate and severely damaged/collapsed buildings increased as the number of stories increased. It can be said that there is a significant relation between the number of stories and the level of damage. In the earthquakes experienced in Türkiye in 2023, it was stated that the damage rate increased with the increase in building weight as expected in high-rise buildings [46].

The other parameter used in the calculation is the concrete compressive strength. Since most of the buildings used in this study were constructed before 2000, i.e., before ready-mixed concrete, their concrete compressive strengths are much lower than the values required by the seismic codes. In TEC-1997 [55], it is mandatory to use concrete with a minimum strength of 20 Mpa (C20) in reinforced concrete buildings in 1st and 2nd degree earthquake zones and 16 Mpa (C16) in 3rd and 4th degree earthquake zones. In TEC-2007 [56], it is stated that the minimum concrete compressive strength should be C20/25. According to TBEC-2018 [25], C25/30 for ready-mixed concrete and C30/37 for precast concrete elements are mandatory. After the earthquakes in Türkiye in 2023, it was determined that the concrete properties of most buildings were not in accordance with the regulations at the time of construction. Inappropriate aggregate distribution, aggregates with rounded surfaces, low cement ratio, and unplaced and unvibrated concrete were reported [47-50]. Only 8 buildings considered in this study met the code regulations. It was found that as the concrete strength increases, the number of buildings with low and moderate damage fluctuates while the number of buildings with severe damage decreases.

Another parameter affecting the building behavior and used in the calculation is the ground floor area. In the buildings considered in this study, it was determined that the building damage level increased as the ground floor area decreased [3]. After the earthquakes in Türkiye in 2023, it was stated that the size of the ground floor area directly affects the level of building damage [51, 52]. As the ground floor area of the building decreases from 800 m^2 to 200 m^2, the limited damaged building is replaced by a severely damaged or collapsed building.

Building a structural system is one of the main factors affecting earthquake behavior. In this study, this factor is taken into consideration as the ratio of the vertical structural elements (columns and shear walls) at the critical floor (mostly ground floor) to the total floor area above it. It was determined that the damage level increases as the ratio of vertical structural elements decreases. The importance of vertical structural elements was stated in the investigations made after the earthquakes in Türkiye in 2023 [46, 51, 53, 54].

Especially after the February 6, 2023, Kahramanmaraş-Pazarcık (Mw=7.7) and Elbistan (Mw=7.6) earthquakes, it was observed that structural irregularities played an important role in the behavior and negatively affected the damage level of the structure [57, 59]. According to TBEC-2018 [25], irregularities are divided into two categories irregularities in plan (Group A) and irregularities in vertical (Group B). In addition, short column, heavy overhang, and frame irregularity parameters, which are not included in this grouping but affect the behavior of the structure negatively, were also considered [57, 59]. It was stated that these irregularities were observed in many buildings in Türkiye after the earthquakes in 2023. It is stated that these irregularities cause serious problems due to architectural and economic requirements and take a role in the collapse of the structure [51, 47, 46, 1, 2, 52, 58]. Irregularities related to weak and soft stories are the frequent irregularities observed in recent earthquakes [59]. The high impact of these irregularities was emphasized in different sources [47, 48, 50, 51]. Of the 192 buildings considered in this study, 86 of them have soft story irregularities. It was observed that 57% of these buildings were severely damaged or collapsed.

The other parameter considered in the calculation is heavy overhang. Heavy overhangs shift the center of mass of the building and increase the effect of earthquake forces acting on the building [59, 60]. Of the 192 buildings considered, 69 buildings have heavy overhangs. 62.3% of the buildings with heavy overhangs are severely damaged or collapsed.

Frame discontinuity is an irregularity that occurs due to design problems and adversely affects the earthquake behavior. This discontinuity is known to cause serious problems [61]. After the earthquakes in Türkiye in 2023, it was reported that frame discontinuity, stub beam, and eccentricity in column-beam joints caused damage to the structure [2, 46]. There are frame irregularities in 120 buildings considered in the study. It was observed that 52.5% of these buildings were severely damaged or collapsed.

The other parameter considered in the study is torsional irregularity. If the center of mass and rigidity of a building are far from each other, torsion occurs when the building rotates around its axis. In the case of torsional irregularity, additional shear forces occur in the structural system elements [64]. In the investigations conducted after the earthquakes in Türkiye in 2023, it was stated that many buildings were affected by torsion due to factors such as heavy overhang, vertical element irregularity, plan irregularity, serious damage, or collapse [47, 51].

2.3. Method

2.3.1. Zadeh's Principles of Fuzzy Logic

It can be stated that the principles of fuzzy logic became more evident with Lotfi A. Zadeh's work "Fuzzy Algorithms for Complex Systems and Decision Processes" in 1973 [29]. The fuzzy logic approach created by Zadeh with linguistic rules was stated by Mamdani that it can be easily processed in a computer environment [31]. The principles of this method found by Zadeh can be expressed as follows [66]:

- In the fuzzy logic method, approximate values are used instead of exact values.
- For fuzzy logic, information can be defined by data inputs that contain linguistic expressions such as a little, a lot, quite a little, and quite a lot.
- In fuzzy logic, values are represented by a membership degree in the range [0-1]. This means that increases and decreases can be calculated as a function.
- Any logical expression can be transformed into a fuzzy expression.
- Fuzzy logic is an ideal method for solutions when mathematical expressions are too complex and difficult.

2.3.2. Membership Functions and Gaussian Membership Function

The functions that show the degree of belonging of the elements in any set are called membership functions [67]. There is no specific rule in determining membership functions. Generally, the most appropriate function is selected for the data collected in the study for membership functions. Artificial neural networks and genetic algorithms can also be used in the selection of membership functions [67]. The membership functions developed to date and used in many fields are triangular, trapezoidal, Gaussian, S, and sigmoidal functions. Gaussian membership function is used in this study (Equation 1). In the equation, m is the center of the function and σ is the standard deviation of the function. The function lies between 0 and 1. As the standard deviation increases, the graph widens and as it decreases, the graph narrows. A graphical representation of a Gaussian membership function is given in Figure 1.

$$\mu_H(x; m, \sigma) = e^{\frac{-(x-m)^2}{2\sigma^2}} \qquad (1)$$

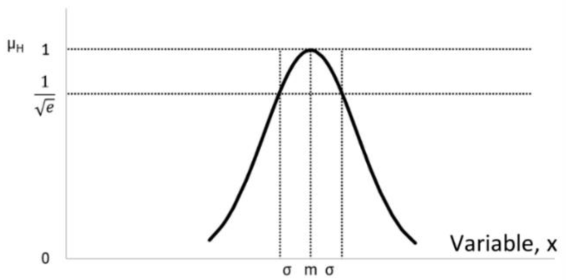


Figure 1. Gaussian Membership Function

2.3.3. Fuzzy Inference Systems

Fuzzy logic principles are established in a systematic way and fuzzy logic inference is performed with the given input information. The inference process against the given input information forms the basis of the method. The inference process is named fuzzy rule-based systems, fuzzy expert systems, fuzzy modeling, fuzzy associative memory, fuzzy logic controllers, and simple-variable fuzzy systems [65]. Inference systems have been used as an alternative to logic and probability theory. Unlike the classical set, instead of inferring that the elements belong or do not belong to the set, they can be expressed by a membership function that infers values between 0 and 1. The biggest feature that distinguishes fuzzy logic from other methods is that verbal terms are expressed in numerical terms [69]. Fuzzy inference systems combine fuzzy values using logical rules (if-then), binding operations (and, or, not), and mathematical operators (+, -, *, /, min, max) [70]. The most widely used fuzzy inference system is Mamdani fuzzy inference [30]. Figure 2 shows the rule base. The fuzzy inference system consists of subsystems and its schematic drawing is given in Figure 3 [71, 72, 77]. Inference is made in accordance with the subsystem order. These subsystems are given below.

- Defining if-then rules
- Defining the database
- Defining the membership functions of fuzzy sets
- Defining the inference unit for a given rules result
- Combining the given information with verbal variables and membership degrees, defining the fuzzification interface
- Defining a fuzzification interface for converting fuzzy results into precise outputs

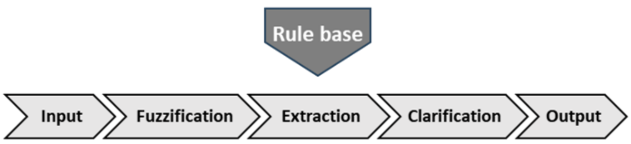


Figure 2. Gaussian Membership Function

2.3.4. Fuzzification and Rule Base

The transformation of the data to be processed with the rule base into symbolic values that are linguistic qualifiers is called fuzzification [31]. Input information is processed with the first fuzzification phase. In this unit, the input and output information are fuzzified by converting it to a certain value with the specified membership function [67]. Fuzzification is a step that connects the data with if-then rules [73]. The logical binding of input and output information forms the rule base of fuzzification [72]. In this context, input and output information are bound together. The rule base is available in all coding languages used nowadays.

2.3.5. Inference Unit and Mamdani Type Fuzzy Inference

A fuzzy inference unit is a collection of operations that collects and presents input and output information with a rule base [74]. It can also be considered as filtering the information with a rule base [75]. The most widely used inference rules in the literature are the Mamdani and Takagi and Sugeno inference approaches. The most widely used fuzzy inference is Mamdani type inference [30]. This method is widely used because it is easy to create and suitable for human behavior. It can be said that the Mamdani type is the basis of other inference methods [76]. A graphical representation of the Mamdani fuzzy inference method using minimum and maximum operators is given in Figure 3. The following rules can be given as examples of the use of minimum and maximum operators.

- Rule 1: If x = K1 and y = L1, then z = M1.
- Rule 2: If x = K2 and y = L2, then z = M2.

Here x and y are the digital input elements and z is the output element.

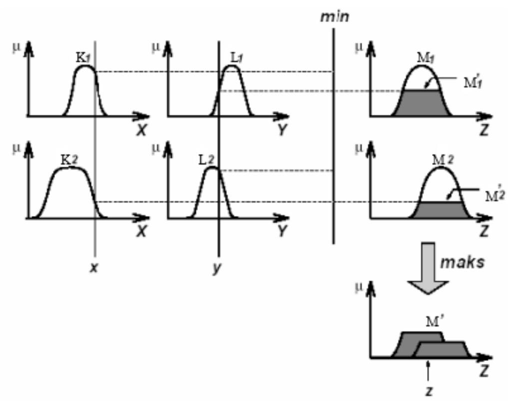


Figure 3. Mamdani fuzzy inference using fuzzy minimum and maximum operators [77].

2.3.6. Defuzzification and Center of Gravity Method

The last unit of the fuzzy inference method is defuzzification. In this unit, the verbal data from the inference unit is expressed numerically. There are many different methods such as the average of the largest, center of gravity method, and maximum membership center method. Although all defuzzification methods (except for the smallest of the maximum and largest of the maximum) give similar results, for quantitative decisions like prioritization center of gravity method is recommended [73]. The most commonly used defuzzification method among these methods is the center of gravity method [70]. In this method, inference is obtained by finding the center of gravity of the combination of membership functions. The center of gravity method is given in Equation 2 and its graphical representation is given in Figure 4. Where k is the union of the fuzzy sets during the application of Mamdani and Larsen inference, z_i is the i'th element of the fuzzy union set, and z* is the rationalized value [79].

$$z^* = \frac{\sum_{i=1}^{n} z_i \mu_k(z_i)}{\sum_{i=1}^{n} \mu_k(z_i)} \quad (2)$$

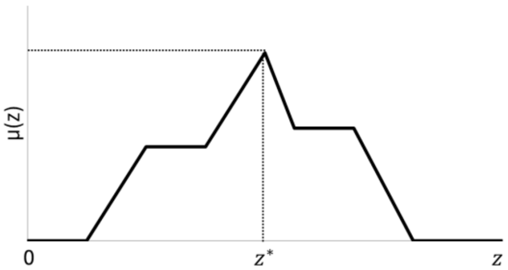


Figure 4. The center of gravity method

2.4. Fuzzy Logic Method for Determining Building Performance

The Matlab program was used to determine the seismic performance of the considered buildings. In the program, the effective parameters considered with the help of the toolbar are defined in the "Matlab Fuzzy Logic Toolbox". In the performance calculation, concrete strength (fc), ground floor area (Af), structural system element ratio ((Ac+Asw)/Aft), number of stories and irregularities (heavy overhang, short column, frame discontinuity, soft/weak floor, torsion) were defined as membership functions. Figure 5 shows the fuzzy logic method diagram and Figure 6 shows the membership functions of the parameters. A preliminary analysis was performed to find the range of the membership functions. Finally, it was seen that the best result was found with the Gaussian membership function.

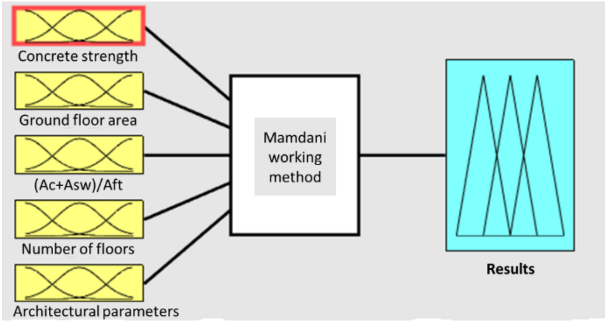
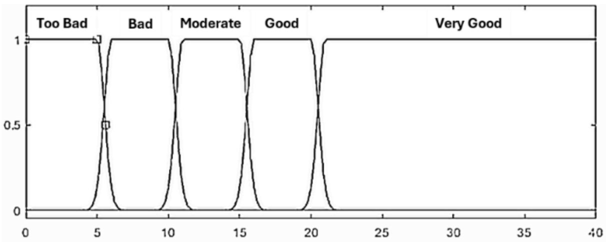
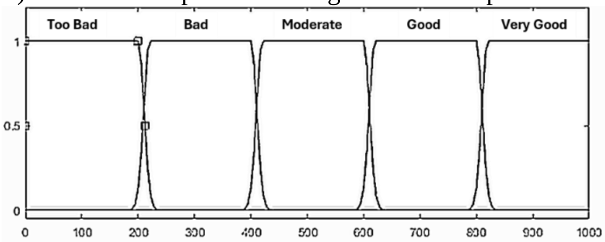


Figure 5. Fuzzy logic method used in the study

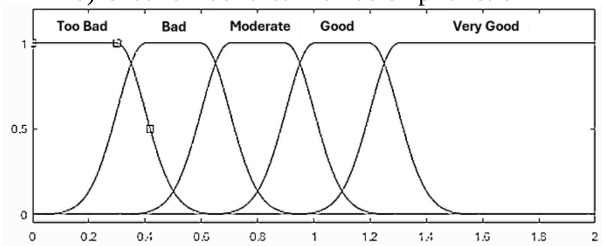
The membership function used for concrete compressive strength in the fuzzy logic method is given in Figure 6a. Concrete compressive strength was scored as too bad if between 0-5 MPa, bad if between 5-10 MPa, moderate if between 10-15 MPa, good if between 15-20 MPa, and very good if between 20-40 MPa. In the method, the ground floor area parameter was scored from small to large (Figure 6b). Scoring is given as too bad, bad, moderate, good, and very good. If the ground floor area of the building is smaller than 200 m^2, it is scored as too bad, if it is between 200-400 m^2 it is scored as bad, if it is between 400-600 m^2 it is scored as moderate, if it is between 600-800 m^2 it is scored as good and if it is larger than 800 m^2 it is scored as very good. The ratio of the total area of columns and shear walls on the ground floor to the total floor area was scored as too bad, bad, moderate, good, and very good (Figure 6c). This ratio is defined as too bad if it is less than 0.3%, bad if it is between 0.3-0.6%, moderate if it is between 0.6-0.9%, good if it is between 0.9-1.2%, and very good if it is greater than 1.2%. If the number of stories is 2 or less, it is scored as very good, 3 as good, 4 as moderate, 5 as bad, and 6 or more as too bad (Figure 6d). Since irregularities negatively affect the building behavior, they were scored with the membership function. Here, the scoring was changed according to whether the buildings had irregularities such as short columns, frame irregularities, torsion, heavy overhang, weak floor, and soft floor. Irregularities were calculated as negative and an initial score of +5 was given for irregularities. For each irregularity, 1 point was subtracted from the initial value. The remaining score gave the building a score for the irregularities. The scoring was determined as too bad, bad, moderate, good, very good. In this context, if the building has no irregularities or 1 irregularity, it is scored as very good, 2 irregularities as good, 3 irregularities as moderate, 4 irregularities as bad, and 5 irregularities as too bad (Figure 6e).



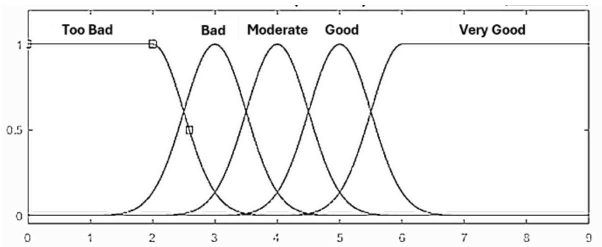
a) Concrete compressive strength membership function



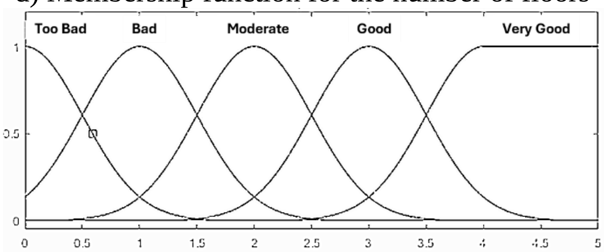
b) Ground floor area membership function



c) Membership function for the ratio of total column and shear wall area to total floor area at the ground floor



d) Membership function for the number of floors



e) Membership function of architectural parameters

Figure 6. Membership functions

The membership functions are combined with the rule base to produce the final membership function (Figure 7). In the final membership function, a triangular membership function was used since the results should be accurate for building performance. For the results, it was determined that the most appropriate method for the rinsing unit was the center of gravity method. Considering TBEC-2018 and RYTEIE-2019, the resulting membership function was divided into 4 damage states (collapse, severe damage, moderate damage, and limited damage) [9, 25]. If the resulting damage score from the building membership functions is in the range of 0-0.2, the building is collapsed, if it is in the range of 0.2-0.4, the building is in a severe damage state, if it is in the range of 0.4-0.6, it is in moderate damage state, and if it is in the range of 0.6-0.8, it is in limited damage state.

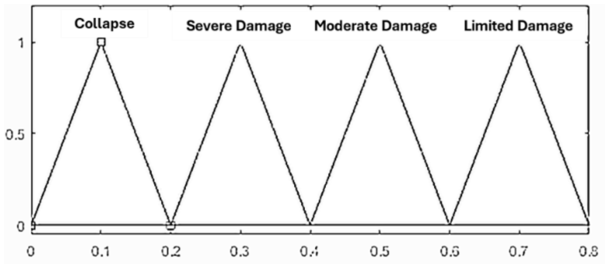


Figure 7. Result membership function

2.5. Training The Fuzzy Logic Rules

In the Matlab program "Fuzzy Logic Toolbox", membership functions were written according to if-then rules considering the actual building damage status. Mamdani inference method was used in these rules [30]. After the rules, the center of gravity method was used as a defuzzification method. 94 buildings' data were selected blindly and used in the training stage. Although several other building parameters affecting the vulnerability of a building (for example plastic hinge state was mentioned to be crucial) may be utilized in the training process [42], training can also be done with the limited data given in this study. The following 8 rules are given as examples:

- If (concrete strength is very good) and (ground floor area is very good) and ((Ac+Asw)/Aft is very good) and (number of stories is very good) and (no irregularities, i.e. irregularities are very good) then (result is limited damage)
- If (concrete strength is moderate) and (ground floor area is moderate) and ((Ac+Asw)/Aft is very good) and (number of stories is very good) and (irregularities are very good) then (result is limited damage)
- If (concrete strength is good) and (the ground floor area is too bad) and ((Ac+Asw)/Aft is bad) and (the number of stories is good) and (irregularities are very good) then (the result is moderate damage)
- If (concrete strength is good) and (ground floor area is bad) and ((Ac+Asw)/Aft is bad) and (the number of stories is good) and (irregularities are moderate) then (the result is moderate damage)

- If (concrete strength is good) and (the ground floor area is bad) ((Ac+Asw)/Aft is moderate) and (the number of stories is too bad) and (irregularities are good) then (the result is severe damage)
- If (concrete strength is moderate) and (the ground floor area is good) and ((Ac+Asw)/Aft is bad) and (the number of stories is bad) and (irregularities are bad) then (the result is severe damage)
- If (concrete strength is bad) and (ground floor area is bad) and ((Ac+Asw)/Aft is moderate) and (number of stories is moderate) and (irregularities are moderate) then (result is collapse)
- If (concrete strength is bad) and (the ground floor area is bad) and ((Ac+Asw)/Aft is bad) and (the number of stories is too bad) and (irregularities are very good) then (the result is collapse)

3. Results and Discussion

The seismic performance of a building depends on many parameters and in post-earthquake investigation reports, several reasons were mentioned related to the collapsed or severely damaged buildings [57, 59]. A building that collapsed for only one reason is rarely encountered. Therefore, determining the seismic performance of buildings with complex systems and many parameters requires time and cost. In this context, some studies in the literature have tried to predict the seismic performance of buildings by scoring with a limited number of parameters. Especially in the second-level evaluation methods, important parameters related to the seismic performance of buildings are required to calculate the performance score of the building to determine whether it will exhibit limited, moderate, or severe damage.

In this study, 192 buildings that experienced the Van, Afyon, and Bingöl earthquakes were processed with fuzzy logic method and compared with the second level evaluation methods proposed by Hassan and Sözen (1997), Otani (2000), JBDPA (2001), Yakut (2004), Tezcan et al. (2011) and Erdil and Ceylan (2019) [3, 11, 13, 14, 16, 20]. In order to make the comparison, the performance levels are basically divided into two: low damage risk and high damage risk. Two damage risk levels determine whether the building can be used after the earthquake or not. According to the studies where the results are compared, it is stated that undamaged buildings can be used immediately, limited damaged and moderately damaged buildings can be used after retrofitting or strengthening, but severely damaged and collapsed buildings cannot be used. Therefore, limited damaged and moderately damaged buildings are considered a low damage risk (LDR) while severely damaged or collapsed buildings are considered a high damage risk (HDR).

3.1. Evaluation of Existing Studies

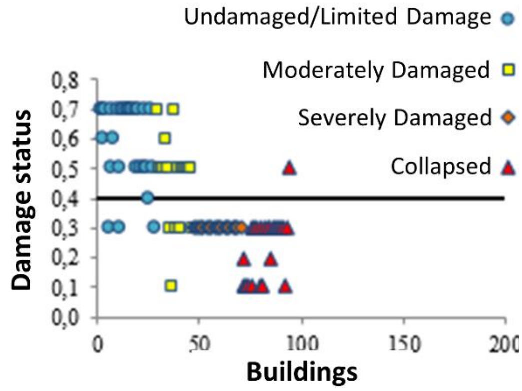
In order to determine the reliability of the fuzzy logic method discussed in this study, 192 buildings should be tested with other existing studies. Hasan and Sözen method (1997) is quite simple to use. Building performance is estimated with 4 parameters of the building. This method, which aims to determine quickly and easily, has an important place in forming the basis of second-level evaluation methods. When these buildings were tested according to the Hassan and Sözen method (1997), 80.6% success was observed in the earthquake performance of buildings in the low damage risk (LDR) category and 53.2% in the high damage risk (HDR) category [3, 11]. In total, 67.2% success was achieved in determining the earthquake performance of buildings. When 192 buildings were tested with the Otani method and the results were compared, 97.9% success was obtained in the HDR category and 29.6% in the LDR category [3, 13]. The total correct prediction of this method in building performances was 63%. In Japan, where many earthquakes have been experienced and earthquake research has been conducted, the Japanese Seismic Index method (JBDPA-2001) was developed to determine building performances [14]. This method is based on the concept of equal energy and is a three-stage method. For performance prediction, 16 parameters of the building are used. As a result, while 100% of the buildings in the HDR category were successfully predicted correctly, 29.6% of the buildings in the LDR category were predicted correctly. In total, 64.1% of the earthquake performance of 192 buildings was predicted correctly. Since this method was developed according to the quality of buildings in Japan, it can be said that the limited values taken into account in the method are not valid for the buildings in Türkiye due to the difference in technical structure and structural system. Yakut method [16] made 91.5% successful prediction in the HDR category and 36.7% in the LDR category. Total success in all buildings was found to be 63.5%. According to the results of the P25 method [20], 79.8% of correct prediction was found in the HDR category and 71.4% in the LDR category. The total correct prediction was calculated as 75.5%. Erdil and Ceylan (2019) [3] tried to determine the seismic performance of the building with the MVP method developed in their study. From this method, 89.4% success in the HDR category and 88.8% success in the LDR category was achieved. Finally, 89.1% of the investigated 192 buildings' seismic performance were predicted correctly.

3.2. Fuzzy Logic Method

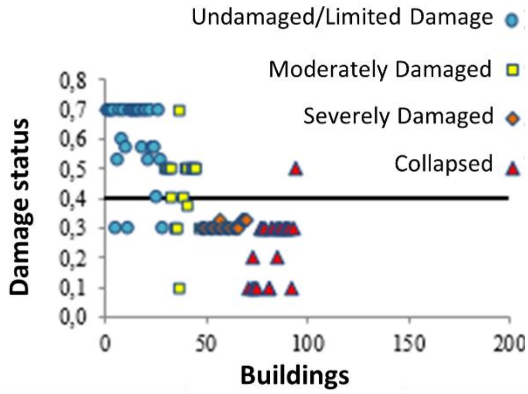
As previously stated, 98 buildings'data were used for training and 94 buildings' data were utilized for testing. 10 parameters were considered in the study. Mamdani method was used as a fuzzy inference system. The membership function types and value ranges that make the study unique and reliable were determined through preliminary experiments as described in the following sections.

3.2.1. Selection of Membership Functions

Gauss, triangular, and trapezoidal membership functions were selected in preliminary tests to determine the membership function types. Not all buildings were tested since the success of the triangular membership function results was found to be low. In the calculations made with the trapezoidal membership function, among the 94 buildings tested, the correct prediction in the HDR category was 97.8%, while the correct prediction in the LDR category was 76.1%. In total, 86.9% of the buildings were correctly predicted. When the Gaussian membership function was used, the correct prediction in the HDR category was 97.8% while the correct prediction in the LDR category was 76.1%. Figure 8 shows the buildings and their damage levels. The results were the same for the two different membership functions. It was observed that the building damage scores changed with the membership functions, but since they were close to each other, they were in the same result range. Although the same results were obtained in a preliminary analysis, the Gaussian membership function was selected. Figures 8a and b show the building results according to the two membership functions. As can be seen from the figures the damage level of 0.4 is set as the boundary line, stating that the region above this line is called LDR and the region below this line is called HDR. The LDR region contains limited damage and moderate damage states of buildings, while the HDR region contains severe damage states and collapsed buildings. Comparing both figures, changes in the distribution of limited damaged buildings and moderately damaged buildings can be seen. Although there are changes in the scoring, the final assessment remains the same. For example, buildings between 0.4 and 0.6 were considered to be moderately damaged. Some error warnings were also received for some buildings which are because of the buildings with similar characteristics that were identified in the collapsed area. In this case, even though such buildings were moderately damaged, they were perceived as collapsed buildings according to the method. This situation was mostly observed in buildings with a moderate damage state.



a) With the Gauss membership function



b) With Trapezoidal membership function

Figure 8. Buildings and damage states

3.2.2. Determination of Membership Function Ranges

The intervals for the selected Gauss membership function should be determined in a way that increases the percentage of success in damage state prediction. In this context, the best results for the seismic performance of buildings were determined by expanding and narrowing the ranges. Table 2 shows the ranges obtained by widening the membership function values. For example, concrete strength is assumed to be too bad up to 10 MPa and very good if it is more than 25 MPa. Except for the irregularities, other values were widened in the same way. As a result, 97.8% of the buildings in the HDR category were correctly predicted. However, the successful prediction of the buildings in the LDR category decreased to 52.2%. The damage status of all buildings was correctly estimated at 74.9%.

Table 2. Ranges in case of widening the membership function values

Concrete Compressive Strength		Ground Floor Area		Number of Stories	
$0<f_c\leq10$	Too bad	$A_f\leq300$	Too bad	≥7	Too bad
$10<f_c\leq15$	Bad	$300< A_f \leq500$	Bad	6	Bad
$15<f_c\leq20$	Moderate	$500< A_f \leq700$	Moderate	5	Moderate
$20<f_c\leq25$	Good	$700< A_f \leq900$	Good	4	Good
$25<f_c$	Very good	$900< A_f$	Very good	≤3	Very good
$(A_c+A_{sw})/A_{ft}$			Irregularities		
$(A_c+A_{sw})/A_{ft} \leq0.4$	Too bad		0-1	Too bad	
$0.4< (A_c+A_{sw})/A_{ft} \leq0.7$	Bad		2	Bad	
$0.7< (A_c+A_{sw})/A_{ft} \leq1.1$	Moderate		3	Moderate	
$1.1< (A_c+A_{sw})/A_{ft} \leq1.3$	Good		4	Good	
$1.3<(A_c+A_{sw})/A_{ft}$	Very good		5	Very good	

The results obtained by increasing the membership function values are given in Figure 9. It is seen from the figure that almost half of the undamaged/limited damaged and moderately damaged buildings are in the HDR region. As can be seen from these ranges, when the critical ranges of the parameters were increased, most of the buildings fell into the HDR category. This may mean staying on the safe side, but it leads to a wrong estimate of the final prediction. Since the aim of this study is to estimate the existing damages, it was decided not to widen the ranges.

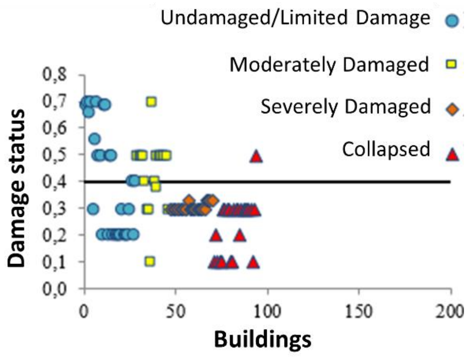


Figure 9. Building damages as a result of widening membership function ranges

The opposite results were observed when the Gauss membership function ranges were narrowed. The values of the narrowed function ranges are given in Table 3 and the building results are given in Figure 10. The function ranges were narrowed, and it became difficult to determine the building damage level. For this reason, it was observed that the severely damaged and collapsed buildings were at the same level as the buildings with moderate and limited damage. As seen in Figure 12, the majority of the buildings remained in the LDR zone. The damage to all buildings in the LDR category was correctly estimated. However, a 4.2% correct prediction was made in the HDR category. As a result of narrowing the range, it is seen that the buildings will perform well, and the damage estimation will be far below reality. Overall correct estimate reached only 52.1%. Since this result is unrealistic, it was concluded that the membership function values should not be narrowed.

Table 3. Ranges in case of narrowing membership function values

Concrete Compressive Strength		Ground Floor Area		Number of Stories	
$0<f_c\leq3$	Too bad	$A_f\leq100$	Too bad	≥5	Too bad
$3<f_c\leq8$	Bad	$100<A_f \leq300$	Bad	4	Bad
$8<f_c\leq13$	Moderate	$300<A_f \leq500$	Moderate	3	Moderate
$13<f_c\leq18$	Good	$500<A_f \leq700$	Good	2	Good
$18<f_c$	Very Good	$700<A_f$	Very Good	1	Very Good
$(A_c+A_{sw})/A_{ft}$			Irregularities		
$(A_c+A_{sw})/A_{ft} \leq0.2$	Too bad		0-1	Too bad	
$0.2<(A_c+A_{sw})/A_{ft} \leq0.5$	Bad		2	Bad	
$0.5<(A_c+A_{sw})/A_{ft} \leq0.8$	Moderate		3	Moderate	
$0.8<(A_c+A_{sw})/A_{ft} \leq1.1$	Good		4	Good	
$1.1<(A_c+A_{sw})/A_{ft}$	Very Good		5	Very Good	

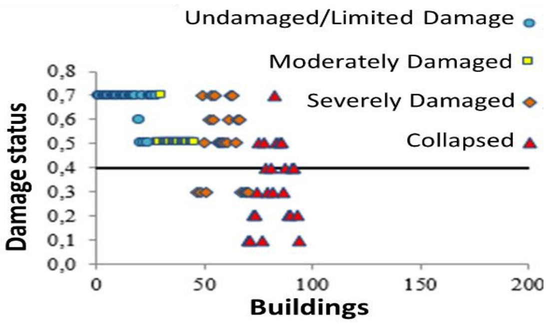


Figure 10. Building damages as a result of increasing membership function values

As a result, determining the value ranges directly affects the reliability of the study. For this reason, it was decided to use the ranges determined by Erdil and Ceylan (2019) [3] for the membership function ranges (Table 4). The study was reorganized for this value range. When the function ranges were averaged, it was seen that the results were closer to the actual performance of the building and were consistent.

Table 4. Function data ranges used in the study

Concrete Compressive Strength		Ground Floor Area		Number of Stories	
$0<f_c\leq 5$	Too bad	$A_f\leq 200$	Too bad	≥ 6	Too bad
$5<f_c\leq 10$	Bad	$200<A_f\leq 400$	Bad	5	Bad
$10<f_c\leq 15$	Moderate	$400<A_f\leq 600$	Moderate	4	Moderate
$15<f_c\leq 20$	Good	$600<A_f\leq 800$	Good	3	Good
$20<f_c$	VeryGood	$800<A_f$	Very Good	≤ 2	Very Good
$(A_c+A_{sw})/A_{ft}$				Irregularities	
$(A_c+A_{sw})/A_{ft}\leq 0.3$	Too bad			0-1	Too bad
$0.3<(A_c+A_{sw})/A_{ft}\leq 0.6$	Bad			2	Bad
$0.6<(A_c+A_{sw})/A_{ft}\leq 0.9$	Moderate			3	Moderate
$0.9<(A_c+A_{sw})/A_{ft}\leq 1.2$	Good			4	Good
$1.2<(A_c+A_{sw})/A_{ft}$	Very Good			5	Very Good

3.2.3. Determination of the Defuzzification Method

Preliminary evaluations showed that the center of gravity method is the most suitable method for the study. In addition, the bisector method was also tried for the defuzzification phase. Using the bisector method, 100% of the buildings in the HDR category and 72.91% in the LDR category were correctly predicted. Considering all predictions, the correct estimate reached to 86.45% of all buildings. Figure 11 shows the results obtained by using the area angle bisector method. Since the center of gravity method attained higher overall correct predictions, it was used for the defuzzification stage.

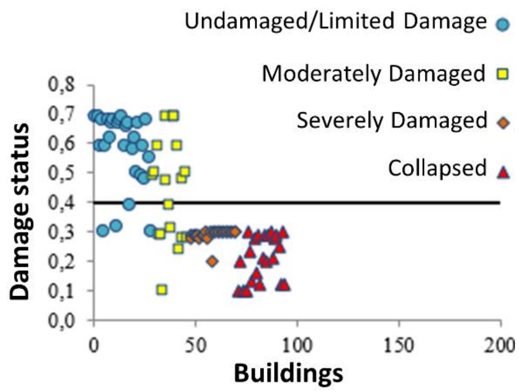


Figure 11. Results obtained by using the area angle bisector method

3.2.4. Proposed Fuzzy Logic Method

The fuzzy logic method as previously noted needs several assumptions related to the fuzzification and defuzzification stages. The reasonable assumptions increase the reliability of the results. Since the aim of this study is to utilize the fuzzy logic method to predict the seismic performance of reinforced concrete buildings, the rational assumptions associated with the building properties, range of the properties, membership functions, and defuzzification methods were sought and the results were summarized in Table 5. As can be seen from the table, with the selected building parameters (concrete compressive strength, ground floor area, number of stories, ratio of the vertical load carrying members at the ground floor to the total floor area, irregularities) and selected ranges as proposed in [3] using Gaussian membership function for fuzzification and center of gravity method for defuzzification, higher correct estimate percentage can be attained.

Table 5. Correct estimate comparison related to fuzzy logic solution assumptions

Membership function	Range of the variables	Defuzzification method	Correct Estimate, %		
			Overall	HDR	LDR
Gauss	**Medium**	**Center of gravity**	**86.9**	**97.8**	**76.1**
Trapezoidal	Medium	Center of gravity	86.9	97.8	76.1
Gauss	Medium	Bisector	86.5	100.0	72.9
Gauss	Wide	Center of gravity	74.9	97.8	52.2
Gauss	Narrow	Center of gravity	52.1	4.2	100.0

3.3. General Comparison of The Methods

Table 5 presents the correct estimate percentages of different preliminary (level two) methods as well as the fuzzy logic method proposed herein. 97.8% of the buildings in the HDR category and 76.1% of the buildings in the LDR category were predicted correctly using the fuzzy logic proposed in this study. In addition, 86.9% of all buildings were predicted correctly. It was observed that the results of the fuzzy logic method reached the most accurate prediction after the MVP method. It can be said that this prediction value is quite high compared to other methods. The results were found to be close to the MVP method. However, since it is a simple and fast method, it can be said that it can be more efficient with additional training and testing building data.

Table 6. Comparison of existing studies and fuzzy logic method

Preliminary Methods	Correct Estimate, %		
	Overall	HDR	LDR
Proposed Fuzzy Logic	**86.9**	97.8	76.1
MVP Method [3]	**89.1**	89.4	88.8
P25 Method (2011) [20]	**75.5**	79.8	71.4
Hassan and Sözen (1997) [11]	**67.2**	53.2	80.6
JBDPA (2001) [14]	**64.1**	100.0	29.6
Yakut (2004) [16]	**63.5**	91.5	36.7
Otani (2000) [13]	**63.0**	97.9	29.6

4. Results

The fuzzy logic method is used to predict the seismic performance of 192 buildings covered in this study. For this purpose, 98 buildings' properties were processed as training data while 94 buildings were used for testing. The following conclusions were drawn from the study:

- Considering the building parameters such as concrete compressive strength, ground floor area, number of stories, the ratio of the vertical load carrying members at the ground floor to the total floor area, and irregularities only, the fuzzy logic method is found to be insensitive to the membership function. Either Gauss or trapezoidal membership functions reached the same correct estimate rate.
- The fuzzy logic method is highly sensitive to the data range of the building properties. If the data range is narrowed more buildings fall into low damage risk region indicating the false prediction of adequate seismic performances. On the contrary, when the data range is widened, then more buildings are placed in high damage risk indicating the inadequate seismic performance of most of the buildings. Although this result seems to be on the safe side, the estimates are not correct.
- Compared to other methods, the fuzzy logic method with the proposed parameters was found to be able to predict the damage state of the reinforced concrete buildings accurately with 86.9% and achieved better results than most of the preliminary methods available in the literature.

Since the fuzzy logic method is directly dependent on the selected functions and the value ranges of these functions, both functions and value ranges should be selected appropriately. The results were estimated with acceptable accuracy using less data than some of the second-stage assessment methods in the literature. In addition, since the fuzzy logic method uses a computer to process the building data, hand calculation errors are avoided, and fast analysis is possible. This can increase the speed of damage assessment studies and reduce the transaction cost. As a result, it can be concluded that the fuzzy logic method is simple, fast, and reliable. With this method, damage levels of buildings after an earthquake can be determined quickly and early intervention can be provided.

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Contributions of the authors

Yıldız: conceptualization, data collection, formal analysis, visualization, software development, ınterpretation of results

Kıpçak: methodology, literature review, ınterpretation of results, writing-first draft, revision

Erdil: project administration, conceptualization, methodology, formal analysis, supervision, revision

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study complies with research and publication ethics

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