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## Measuring the post-earthquake buildings' damage using fuzzy logic

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### ABSTRACT

This research has provided a fuzzy-logic-based method to measure the buildings' damage after earthquake. In this method, the damage level is obtained from the data reported by the trained staff and observations made over the visual parameters such as "structural components" and "non-structural components". Considering the standard assessment form, the damages in each structure are graded from D1 (with no damage) to D0 (destruction). Therefore, this study aims to provide a report on the damage level in the range of D1 to D0. The present study checks the effects of the number and weight of fuzzy logic. Also, the influence of the values related to the membership functions on the overall damage level is evaluated by using the single-index weighted fuzzy rule and the damage level with the highest membership value are evaluated, while the rest of damages are also considered despite their low impact. A genetic algorithm has also been used for optimizing the weights related to the structure's damage. The compiled database covering more than 30 thousand buildings has been used for training and evaluating. Theoretical prediction obtained from the automated processing for assessment forms in each building is compared with the total level of damage (the observed damage) and the level of damage is determined by the observers. The results show that the theoretical assessment proportional to the observed values of 90% of the buildings is evaluated.

**Keywords:** earthquake, damage, evaluation, building, rule weight, fuzzy logic, weight fuzzy rule.

### INTRODUCTION

Earthquake is one of the most destructive natural phenomena. It causes considerable damages in many parts of the world (Guha-Sapir et al, 2012). Frequent earthquakes and their consequences in the form of damage have attracted the attention of many researchers and government officials and this has caused developing and expanding the up-to-date rules during the approval of rules to increase the building function during the earthquake. However, many buildings are constructed without considering the earthquake rules and they are mainly more vulnerable to earthquakes and damages.

After an earthquake occurred, the experts conduct post-earthquake assessment surveys to evaluate the caused damages. One of the main goals of these assessments is to evaluate and classify the buildings into various classes according to their damages (Soltani & Keyhani, 2000). Many of damaged buildings especially located at the event of earthquake are vulnerable and dangerous. Insecure buildings should be evaluated and residence in them should be limited. This classification helps to make decision on which buildings are secure for residence and need to be more evaluated for repairing and rebuilding, and both factors are critical for maintaining the building (Boukri et al., 2014).

Effected and subject to damage buildings are usually classified by using the total level of damage. The total damage level is determined considering to the observed damages on each component

of the buildings. These components are mainly divided into two main categories. For instance, “structural components” (pillars, beams, walls, crushes of stones) and “non-structural components (stairs, partition walls, facade, balcony, etc) can be referred. Mechanically, structure components are the most important part because they have the capacity to resist against bending over horizontal and vertical loads which directly refer to the stability and security of the building. Lack of resistance in these components increases the possibility of building destruction.

In other word, non-structure components are no less important because serious damages to these components sometimes imply that the seismic capacity of the building has decreased. Moreover, non-structural components are accompanied with the assurance of building efficiency and their costs indicate the building’s value (Kircher et al, 2020; Wen et al, 2013; Villaverde, 2014). Other risks such as the condition of soil around the building are also considered during the evaluation at various rules (Kircher et al, 2020; Ghobarah et al, 2018).

Several rules and regulations have been proposed on the post-earthquake assessments and seismic vulnerability in the literatures. These rules range from quick separation to full assessment in terms of monitoring (ATC-20, 2012; ASCE, 2014). They have assessment forms filled out by the observers during the assessment through patrol search in the area so that judgement can be made based on them. For example, the damage level, the seismic vulnerability of the building and the efficiency of the building can be mentioned.

However, an integrated assessment of post-earthquake damages is difficult and complicated which is doubted due to many factors. Doubts make the assessments difficult and challenging. Many factors causing doubts are among the topics of concern in the assessments. Therefore, the main factors affecting on huge earthquakes are described, the assessments are conducted in those emergent situations in which there are no enough time and equipment for monitoring. In such situations, observers face may problems to provide valid judgements. Observers have different interpretation of damage index because they interpret visually. The rules related to the classification of damages’ level apply quantitative concepts to describe the extent of damages including “no damage”, “slight damage”, “average damage”, “heavy damage” and “destruction”. Therefore, it can be said that different levels of damage have been proposed and still there is no common definition for the concept of damage level. Moreover, the damage level has usually different categories and no clear definition is provided for it (Belazougui, 2013). Then, ambiguous languages create borders between the damage levels. The provided definition for the damage level is interpreted differently among the observers. Hence, it can be said that it is not possible to tell correctly by visual inspection when the components of a building are damaged. Each of the components has specific characteristics and relative importance to the efficiency, situation, and the behavior during the earthquake. For instance, lower floors have their own special components which are more important than the higher floors. However, our understanding of the characteristics influences on logic of observes during the assessment.

It is always difficult to evaluate the huge buildings. Thus, structure systems of the building should be detected first. The various components of the structure systems have different behaviors during the earthquake. The total damages level is related to the damage level of components at an area. It is challenging to determine the effect of each component on the total response of the structure and the existence of large number of components in a structure makes it difficult for



the observers to determine the level of damage. Therefore, these scenarios may cause many doubts for observers, and it is very important to assess these doubts accurately (Pirizadeh, 2017). Most of the buildings are built with poor quality control. Despite this fact that some buildings may be built with/without considering the modern standards of the construction, these buildings cannot have reliable seismic performance. This information (applicable seismic standards) may sometimes confuse the observers. So, the observer should more focus on his/her engineering judgements. Another factor that arises at the time of building damage is the façade, cover, or architecture of the building while the structure system is intact or the damage level is low. These buildings may confuse the observer and make the building considered as insecure while it is residential (Shakib & Jahangiri, 2016). In other word, other buildings may lack the visual evidences of heavy structure damages and this damage is described through the coverage or other architectural parts of the building. These buildings are considered a real threat for the residents and should be addressed by observers.

Expertized systems are one of most important tools nowadays. These systems are used for solving the complicated problems and helping the experts in decision making. Expertized systems are used widely in almost all the engineering areas. Moreover, these systems use the artificial Intelligence theories (like neural networks, fuzzy logic, Genetic algorithm, rule-based system, knowledge-based systems) and human stored knowledge for invoking and judging the behavior of experts to perform skills and make conclusions (Jackson, 2016; Liao, 2014).

A decision support tool is used during evaluating the seismic threats which can help the observer a lot and minimize the threats. Therefore, several researchers have used artificial intelligence theories to build expertized systems in pre- and post-earthquake assessment models. Many offered methods are used across the world and help the observer in the assessment process. These methods are used by researchers such as Sanchez-Silva & Garcia, Demartinos & Dritsos, Sextos et al, Carreño et al, Tesfamariam & Saatcioglu, Şen, Mebarki et al. However, it is difficult to develop and expand expertized systems alone. These systems with high performance need to expert knowledge and advanced practices in which simple methods are usually useful for developing such systems.

In this study, an automated processing method has been provided to construct fuzzy systems with the application of assessing post-earthquake damages based on fuzzy logic, approximate logic, weighted fuzzy rules and fuzzy inference methods. At this study, the effect of the number and weight of fuzzy rules has been checked while the damage level at the components is related to the damage level at the whole building. The presented method aims to process the damages at the building components to determine the damage level at the whole building.

### **Structural vibration**

Suppose you are standing at a bus and it starts to move, at this time your legs are pulled forward while your body tends to stay still (Law of Inertia Or the first law of Newton's motion). This is exactly the time earthquake is happening and the bases of the building starts to vibrate while the main body of the building tends to preserve its original state.

At the building whose ceiling is stand by the pillars, during the earthquake an inertia force is created in the ceiling which according to the second law of newton's motion is proportional to the mass and acceleration of the roof. Thus, the lighter the structure (less mass), the less the inertia force created in the ceiling and the greater the resistance to the earthquake (Sedaghati et al., 2018).



During earthquake, an inertia force is created in the pillars connected to the ceiling at the opposite direction of building's acceleration causing to bend the pillars. If we consider the horizontal distance below and above the bent pillar as "u", the result is that the greater "u", the greater the inertia force.

The applied inertia force to the building should be transferred from the floors to pillars, walls, foundation and then the land. Thus, each of the components and the connection between them should be designed so that enables to transfer the force. In this regard, pillars and the wall play a more important role in transferring the inertia force while slabs and beams are more important at old buildings. Walls are thin, made by fragile construction materials, and with little thickness, they were weak against the horizontal inertia force of the earthquake.

### **Retrofitting the building**

Scientifically, the term retrofitting is not definitely to enhance the resistance against earthquake, but it means to improve the function of structure's components (building) against the earthquake. For this reason, the term improvement and especially for the earthquake force, the term seismic improvement is more accurate.

Retrofitting a structure is to increase its resistance to the applying forces on it. During the earthquake, many forces are applying on the building which cause severe financial and life losses and even may cause the building collapse if its skeleton and the used material are not resistant enough (Rezaie, 2013).

In retrofitting process, it is tried to enhance the safety of the building and neutralize the negative effects of the applied forces on the structure by using some methods. In this regard, it can be stated that the building has become earthquake-resistant.

### **Which buildings are earthquake-resistant?**

To find out which buildings are earthquake-resistant, it should be noted that at first, structures should be designed and implemented according to the principals and rules of engineering regulations, otherwise it cannot be said that a structure is earthquake-resistant. The buildings mentioned below usually show better resistance against earthquake:

- The building's construction should not be designed and implemented with very high weight; the building's weight is one of the very important points the engineers should consider.
- The buildings with cohesive concrete skeleton in their construction are more resistant to the earthquake.
- The buildings with well-established seismic systems (shear wall, cross brace, etc.) show more resistance against the earthquake (Sadidkhoy, 2011).

### **The necessary measures to construct earthquake-resistant buildings**

Retrofitting the old buildings should be in priority for the engineers and individuals. The statistics show that a low percent of buildings are earthquake-resistant. There is no tool for detecting an earthquake-resistant building, unless investigations are done on some technical characteristics of the building. One of the important points is that to buy a building constructed by an expert team that, in addition to considering the technical regulations, they have used high-quality materials in its construction (Bastami et al., 2012).

### **Implementation of the retrofitting plan**



In this stage, some parts of the building may need to be temporarily evacuated. In private buildings, depending on the building type and the number of floors etc., the whole building may need to be evacuated. The cost for retrofitting includes three parts:

- The cost of first and second stages above, which is almost equal to the cost of redesigning the building.
- The cost of third stage vary depending on the building type and the required retrofitting type and may be one to several times more than the cost for redesigning the building.

The implementation cost: it completely depends on the retrofitting plan but usually it costs more than the same executive operations in under-construction buildings (Rokhzadi, 2013).

### **The effect of earthquake on the reinforced concrete buildings**

Reinforced concrete consists of concrete and steel rods. The concrete is made of sand, crushed stone and cement together with water. The concrete can shape any form and frame; the steel also can shape easily by bending. Concrete buildings are consisted of horizontal (slabs and beams) and vertical (walls and pillars) components. Earthquake creates an inertia force in the building relative to the building's mass and since the most building's mass is placed at the floor (Rezaie et al., 2013).

In multi-story buildings, the thickness of slabs ranges from 11 to 15 cm. when the beam is bent in vertical direction due to earthquake, these thin slabs also bend with the beams and then pillars and beams move in horizontal direction. The slab forces the beam and they move together. In most of buildings, the geometric strain of the slab is neglected which should be considered by the engineers in designing. When a horizontal force is applied to the pillars, they move in horizontal direction while the walls tend to resist against the horizontal motion (Mohammadi & Shaandi, 2015).

Due to heavy weight and thickness of the walls, they reflect more horizontal force. A gap is created in the walls because of fragility of the materials used in them.

In the loaded beam, the middle of the lower surface of the beam is under tension, and in the upper surface of the beam the two ends are under tension. At the load applied to the building by earthquake, the tension occurred in the beams and pillars is different from the vertical loading.

### **Post-earthquake damage evaluation: general aspects**

This research aims to provide a general automated processing method by using at the post-earthquake damage evaluation and assessment form. These forms are filled out after visual monitors on the building after the earthquake.

Assessment forms include some parts of systemizing the assessment method. Each part has some sub-components that are assessed commonly. Moreover, each of these subcategories should be represented by the maximum damage observed in the same category (for example, if different damages are observed in the concrete pillars, the maximum damage should be considered). It is expected that observer should visually inspect the building components and filled out the assessment form based on criteria D1 (no damage) to D5 (destruction). Finally, the observer determines that final damage based on the criteria D1 to D5 and by analyzing the damage determined in the form. The safety and efficiency of the building is also determined by using special colors: green for safety, orange for lack of safety and red for risk (table 3).

The previous research carried out on the probability method and the concept of artificial intelligence network show that the total damage depend on the observed damage in each monitoring parameters (like the "structural or primary" components and "non-structural or



secondary" components) (tables 1 and 2). The total damage in the monitored buildings is written as a function of the component's damage based on the following general formula:

$$DG = DG(d_1, \dots, d_k, \dots, d_{N_c}) \quad (1)$$

$$N_c = N_s + N_{ns} \quad (2)$$

Where  $D_G$  is the total damage,  $d_k$  is the damage in the  $k$  components where  $K=1, \dots, N_c$  and  $N_c$  are the final numbers of the components considered as the monitoring parameters. For example, the structural components (pillars, beams, walls, crushed stones) and non-structural components (Stairs, partition walls, facade, balcony etc.) are indicated by  $N_{ns}$ . This amount of damage ( $D_G, d_k$ ) is placed in the interval [1,5] (referring to table 3).

$$DG \in \{D_1, D_2, D_3, D_4, D_5\} \quad d_k \in \{d_1, d_2, d_3, d_4, d_5\} \quad (3)$$

Table (1) structural components (19,21)

Sloping roof	Apartment roof	Components resistant to the lateral load	Components with vertical load	Non-structural components
Steel base wood base Roof cover concrete-covered roof Roof Metal roof	Resistant concrete Steel joint Wood joint	Mortar walls Concrete walls Resistant concrete frame Steel frame Covering frame Etc.	Mortar walls Concrete walls Concrete pillars Steel pillars Wood pillars Etc.	Uniform concrete walls Pitted concrete walls

Resource: Mebarki et al, 2022; Noura et al, 2017

Table (2) non-structural components

External components	Internal walls' panel	Internal components	Hall
Balcony Separator Hanger Parafit Chimney etc.	Mortar Concrete Metal Etc.	Roof Partition Glass	Concrete Metal Wood

Resource: Mebarki et al, 2022; Noura et al, 2017

Table (3).Description of damage level

Decision	Description	Damage level	Damage sign	
No need to assess	With no damage	No damage ( $D_1$ )	Light green	$D_1, d_1$
No need to remove debris but it needs to repair	Separate non-structure damage, gap in the wall or roof, damage to the water tube, ...	Slight damage ( $D_2$ )	Dark green	$D_2, d_2$

Removing debris till the repair and retrofiting time	Heavy non-structural damage, slight structural damage	Average damage ( $D_3$ )	Light orange	$D_3, d_3$
Removing debris till the repair and retrofiting time	Heavy non-structural damage, important structural damage	Severe damage ( $D_4$ )	Dark orange	$D_4, d_4$
Destruction and removal of debris	Building destruction	Destruction ( $D_5$ )	Red	$D_5, d_5$

Resource: Mebarki et al, 2022; Noura et al, 2017

### Fuzzy logic method: theoretical aspects

#### Theoretical frame

Madman fuzzy system has been used in the theoretical framework of this study and these forms lead to develop the proposed fuzzy logic model (figure 1). In this method the general damage level  $D_G^*$  in the building is determined by the damages observed on the components. For example, the structural and non-structural components are also mentioned in the previous researches (Mebarki et al, 2022; Noura et al, 2017). Moreover, in this method, the results obtained for the structural damage  $D_S^*$  and non-structural damage  $D_{ns}^*$  are provided.

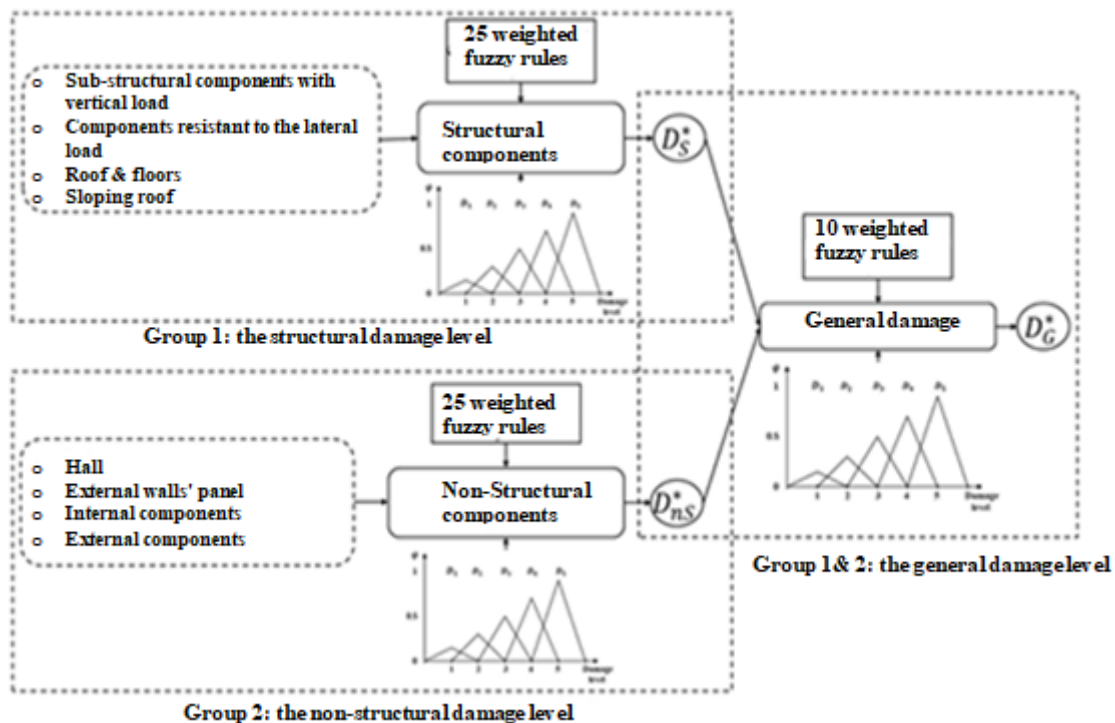


Figure1. Flowchart of the presented fuzzy logic method

Therefore, using the equation 1, the general damage level can be determined by a function of monitoring parameters.

$$DG = DG(1k.dk), k = 1, \dots, Nc \quad (4)$$

Together with

$$1k = \{ 1, 0$$

1: if k is the monitoring parameter. Otherwise = 0.

### Developing and expanding fuzzy parameters

The theoretical framework of the proposed fuzzy logic can be described according to the following steps:

- Selecting fuzzy subsystems (groups) effecting on the general damage level: these parameters indicate the assessed parts in the form. Thus, the groups are selected based on the mentioned parameters in the research. For example, the post-earthquake damage assessment: three groups are considered in this study (figure 1).

Group 1: "structural damage  $D_s^*$ " have 5 components including: structural sub-components SV, vertical components VC, lateral load-resistant components LC, apartment roof, floors FR and sloping roofs SF (table 1).

Group 2: "nonstructural damage  $D_{ns}^*$ " have 4 components including stairs ST, internal components IC, external wall panels and External components EC (table 2).

Group 1-2: "general damage  $D_G^*$ " involving the results from previous groups including "structural damage level" and "non-structural damage level".

- The definition of fuzzy logic parameters": these parameters describe the relation between the damage of components and the final damage level in the building. For this reason, fuzzy sets and their functions should be detected.

Fuzzy sets: for each of the components, the damage level is indicated in the equation 3 by  $A_k$  fuzzy set and its membership function  $\mu(d_k)$ . Thus, fuzzy sets are always defined as pairs (equations 6 and 7). Although various membership functions can be used, the most usable triangular membership functions used in this research are as figure 2 (Mamdani & Assilian, 2013).

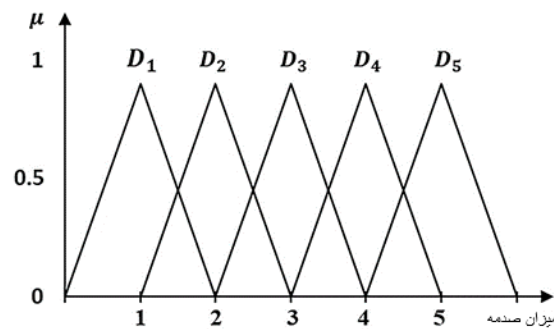


Figure2. Representing the damage level by using triangular membership functions

$$A_k = \{(d_k, \mu(d_k))\} \quad (6)$$

$$\mu(d_k) \in [0,1] \quad (7)$$

The values given in equation 7 (membership values) are selected by the fuzzy system during the evaluation period and according to the observers' data. This fact can be stated that sometimes

observers may confuse and they cannot determine the damage level because the damage level in one component is very high and in adjacent components is low. In this situation, fuzzy logic allows the observers to determine the observed damages at the extent of overlapping (figure 2), general damage  $d_k$  helps the defuzzification proportional to the value of  $\mu(d_k)$  (Van Leekwijck & Kerre, 2019).

Fuzzy rules: it is very important to develop the effective fuzzy rules (IF-THEN) in modeling the fuzzy logic, because they directly effect on the function of system (Wang & Mendel, 2014). Fuzzy rules require appropriate human knowledge with calculative efforts for big data (Ishibuchi et al, 20100. In this study, a new application of weighted fuzzy rules is proposed; weighted fuzzy rules are stated for expressing the relations between the component damage  $d_k$  and the targeted damage level (for example,  $D_G^*$ ,  $D_S^*$ ,  $D_{ns}^*$ ) and are given as weighted damages.

For each of the groups (fuzzy subsystems), fuzzy rules are modeled by using single-factor fuzzy rule (Ishibuchi & Nakashima, 2011) to be able to express short and simple terms:

$$R_j : \text{if } d_k \text{ is } d_0 \text{ then } D^* \text{ is } D_0 \text{ with } w_k, j = 1, \dots, N \quad (8)$$

$$w_k \in [0,1] \quad (9)$$

Where  $d_0$  is the damage observed for components of  $k$  during the visual observation of observers. This stage is one of the probable damages in the assessment.  $D_0$  is the damage determined at the target damage level with the same level as the observed  $d_0$  (tables 3 and 4). The values of  $w_k$  are calculated at the optimization process. Each of the weighted rules can be interpreted as the follow: for example, if the checked component of  $k$  suffers from moderate damage ( $d_k$  equal to  $d_3$ ) it has the same damage level as ( $D^*$  equal to  $D_3$ ) and the weight proportional to it is  $w_k$ . the  $N$  is equal to the number of rules required to the  $k$  component given the damage level. In this research, 5 damage levels of  $D_1$  (no damage) to  $D_5$  (destruction) are determined which require 5 weighted fuzzy rule for each of the components.



#### Theoretical definition of damage level:

The targeted loss level can be defuzzificated by using the concept of centroid (Van Leekwijck & Kerre, 2019), and it is due to similar characteristics. Defuzzification methods are usually selected according to the modeled issue. The various defuzzification methods are also developed like maxima methods in addition to the centroid method (beginning of maxima, end of maxima, average of maxima,...) (Runkler, 2018). However, these methods are not suitable for the current study because they show values that have the highest return and reduce the effect of weight rule at the defuzzification level. The proposed improvements involve modifying the definition provided for the centroid and the weights of rule (Ishibuchi H, Nakashima, 2011; Nauck & Kruse, 2019). Thus, the target damage level ( $D_G^*$ ) is as the following (figure 3):

$$D_G^* = \frac{\sum_{k=1}^{N_c} \mathbf{1}_k \cdot \mu_k(D_k) \cdot D_k \cdot \omega_k}{\sum_{k=1}^{N_c} \mathbf{1}_k \cdot \mu_k(D_k) \cdot \omega_k} \quad (10)$$

The abbreviated form of this equation is as the follow:

$$D_G^* = \frac{\sum_{k=1}^{N_c} \mathbf{1}_k \cdot D_k \cdot \psi_k}{\sum_{k=1}^{N_c} \mathbf{1}_k \cdot \psi_k} \quad (11)$$

Together with

$$\psi_k = \mu_k(D_k) \cdot \omega_k \quad (12)$$

Where  $\psi_k$  is considered as the weight coefficient. This parameter calculates the effect of observed damages in the components proportional to it at the target damage level (for example,  $D_G^*$ ,  $D_s^*$ ,  $D_{ns}^*$ ). The components with high value of  $\psi_k$  have more effect on the target damage level (equations 11 and 12).

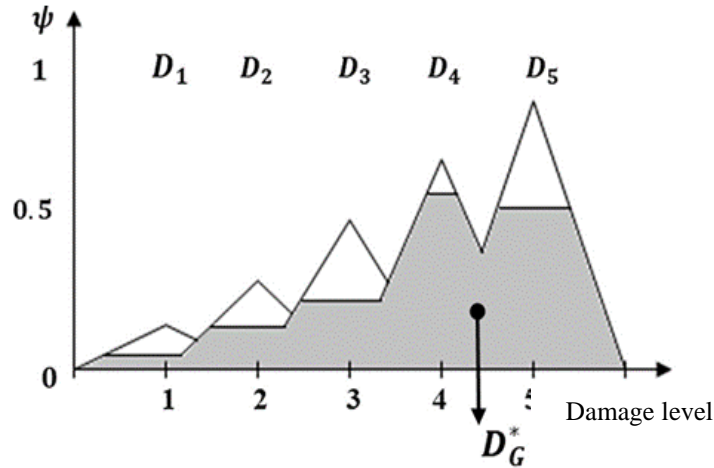


Figure 3. Representing the centroid method used by considering the weighted damage level

#### Weights of fuzzy rules: detection

#### Theoretical developments

The weights of fuzzy rule should be calculated accurately. The experts' comments can be considered as a method for calculating these weights. The values of  $w_k$  are the answers for the following optimization equation:

$$\text{Minimize } X^2 \quad (13)$$

Together with

$$\chi^2 = \frac{1}{N_b} \sum_{i=1}^{N_b} (D_G^*(i) - D_G^{obs}(i))^2 \quad (14)$$

Where  $N_b$  is the number of assessed buildings,  $D_G^*(i)$  is the general predicted damages for the building  $i$  (equation 10), and  $D_G^{obs}(i)$  is the relative general damage level.

The target function reached to the minimize level can be shown as the follow:

$$\chi^2 = \frac{1}{N_b} \sum_{i=1}^{N_b} \left( \frac{\sum_{k=1}^{N_c} \mathbf{1}_k \cdot \mu_k(D_k) \cdot D_k \cdot \omega_k}{\sum_{k=1}^{N_c} \mathbf{1}_k \cdot \mu_k(D_k) \cdot \omega_k} \Big|_{i\text{-th building}} - D_G^{\text{obs}}(t) \right)^2 \quad (17)$$

The optimized values for the weights as the resolves of the optimized problems are presented as the follow:

$$\frac{\partial^2}{\partial \omega_k} = 0, \forall k = 1, \dots, N_c \quad (16)$$

### Optimization process

It is noteworthy that reducing the target function happens complicatedly where the convergence cannot be described. Thus, there is no evidence to show there is an answer. Several optimization methods can be used to achieve the minimal value of general damage at the objective function. Most of the exploratory optimization methods are examined by the proven efficiency like genetic algorithm, particle density (Eberhart & Kennedy, 2013) and direct search (Vitelmo & Haresh, 2017). This method has been used in the current research same as the genetic algorithms method which are efficient and easy to use (Holland, 2020; Whitley, 2022) and the method integrated in MATLAB (MATLAB, 2019).

### Numerical application and example

#### Description of database

Since this research aims to provide an automated process in assessing the post-earthquake damages, the available parameters (Figure 1) during the process are different according to the assessment method and other parameters may be also considered in other applications. A database collected in post-earthquake damage assessment campaigns has been considered.

A database include different situations of the building structures in relation to the lateral covering systems: structures with mortar walls (URM), structures with resistant concrete frames (RCI), structures with resistant tensile walls (RC<sub>2</sub>), steel structures (S) are presented in this database (table 4). Categorizing the buildings are done according to the common methods like HAZUS (Agency' FEM, 2017) used in the previous researches on the city buildings. Database has been selected with the assumption that the assessment forms are accurate and filled out correctly. The monitoring parameters in this study (structural and nonstructural components) have been chosen according to accessing in the database, while other parameters available in the assessment forms (like problems related to the soil around the building) have been neglected and then, the related samples have been removed from database due to lack of suitable samples but these factors were important at the previous researches (Mebarki et al, 2022; Noura et al, 2017). For this reason, it can be stated that the quality of the selected databases can effect on the quality of theoretical results in the automated processes.

Table 4. The distribution of buildings according to the situation and damage level

Type	Damage level					Final	Percent
	D <sub>1</sub> (none)	D <sub>2</sub> (slight)	D <sub>3</sub> (average)	D <sub>4</sub> (severe)	D <sub>5</sub> (destruction)		



RC <sub>1</sub>	62	9823	2883	1091	355	14,214	51,93
RC <sub>2</sub>	0	336	182	57	10	585	2,14
S	1	77	37	21	4	140	0.51
URM	8	5522	3693	1921	1288	12,432	45,42
Total	71	15,758	6495	3090	1657	27,371	100
Percent	0.26	57,57	24,83	11,29	6,05	100	

### Calculation and comparison

To check the performance of the proposed research, database is divided into two categories to perform training (calculation) and validation (validation).

The training database indicating 70% of data (19161 samples) have been used for performing an iterative optimization process so that the weights of the wk fuzzy rule are obtained by reducing the objective function as the average value of  $x^2$  (equation 14). Optimization process provided in the present research is determined as  $x^2 = 0.17$ . It is obvious that the obtained values for the weight of the fuzzy rule are obtained from optimization processes and can be determined proportional to the minimal value of an  $x^2$  objective function. Several optimization processes have been implemented and despite the small differences, the values of weighted fuzzy rule have similarities in the optimization processes.

The determined weights of fuzzy rule for groups (for example group 1, group 2 and group 1-2) are represented at the tables 4 to 6. For the first fuzzy system (group 1: structural damage level) with structural damage level for the level of  $D_s^*$ , the rule weights clearly go from D1 to D5, so that the damage level of D5 have more value for each input variable. Also, the input variables have relatively similar importance because they have almost same weight. Moreover, D3, D4, D5 indicate the high value of all the structural components in comparison with D1, D2 which is very low.

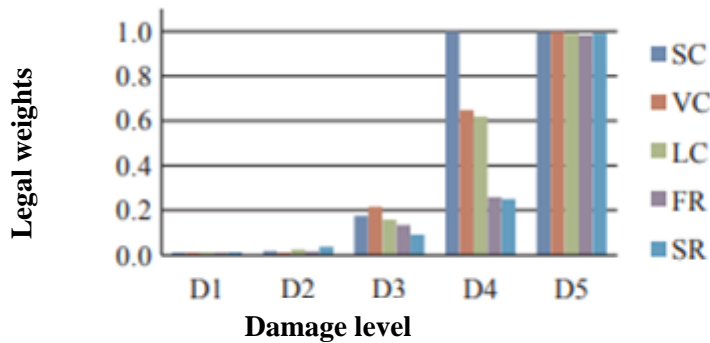


Figure 5. The weight of fuzzy value or  $w_k$  in groups 1 (nonstructural damage)

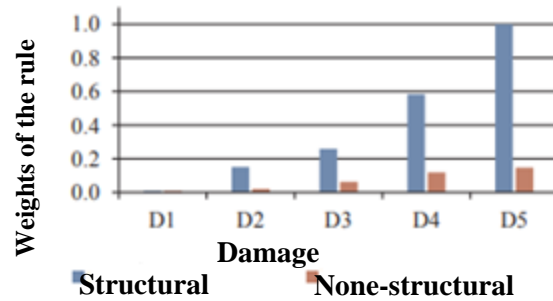


Figure6. The weight of fuzzy value of  $W_k$  in groups 2 (general damage)

In fuzzy system 2 (group 2: non-structural damage level) providing the non-structural damage level ( $D_{ns}^*$ ), the legal weight vary from one variable to another. In fact, there is no clear relationship between data. It can be due to the fact that non-structural components have had less effect on determining the earthquake damage compared to the structural components. Moreover, in the multiple optimization process, non-structural weights have more differences compared to structural parts. This factor is described by effecting on the general damage because the model function is not affected.

Finally, for the final fuzzy systems (group1-2: the general damage level), the legal weight is placed in the intervals of  $D_1$  to  $D_5$  for structural and non-structural damages. Moreover, a clear change can be seen for each of the damage level between the two data. This factor leads to fit with the fact that structural components have more effect on relation to the safety in post-earthquake damage assessment compared to the non-structural components. In addition, comparing each damage level in the structural and non-structural components, the damage level in non-structural components have been accompanied with more weight than structural components. This fact can be described by considering that the expected cost for repairing is affected by the damage level. The greater the damage level, the higher the cost of repairmen and general loss in the building.

Validation database indicating 3% of total data (8210 samples) have been used for validating the obtained  $w_k$  weights to evaluate the accuracy of the proposed model. During the validation, the results from model  $S_G^*$  (theoretical general damage value) have been compared with the results reported by the observers for  $S_G^{obs}$  (the real general damage level). Since all the damage levels are placed in the interval of ( $D_1$ )1 to ( $D_5$ )5, inversion in output values (for example, numerical values) numerically (the damage and safety level) can be accompanied with determining the effective interval for each of the damage and safety values (figure7).

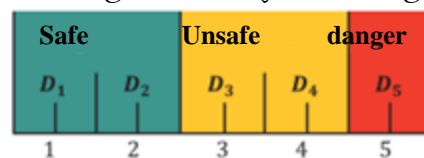


Figure 7. Determining the effective interval for each of the damage levels

The comparison results for the training and validation stage are shown in Figure 8. The proposed method indicates the high performance (90%) during training and validation, and according to these results it is possible to correctly predict how much the total damage is. composition matrix describes the proposed method for each of damage levels (Fawcett, 2016). Each of the diagonal rows shows the expected damage level, while the values outside the diameter indicate the predicted damage level together with error. However, slight decrease in the performance is



observed at the damage level (D<sub>1</sub>: no damage), which could be due to the small number of buildings with this level of damage (0.26% of the database).

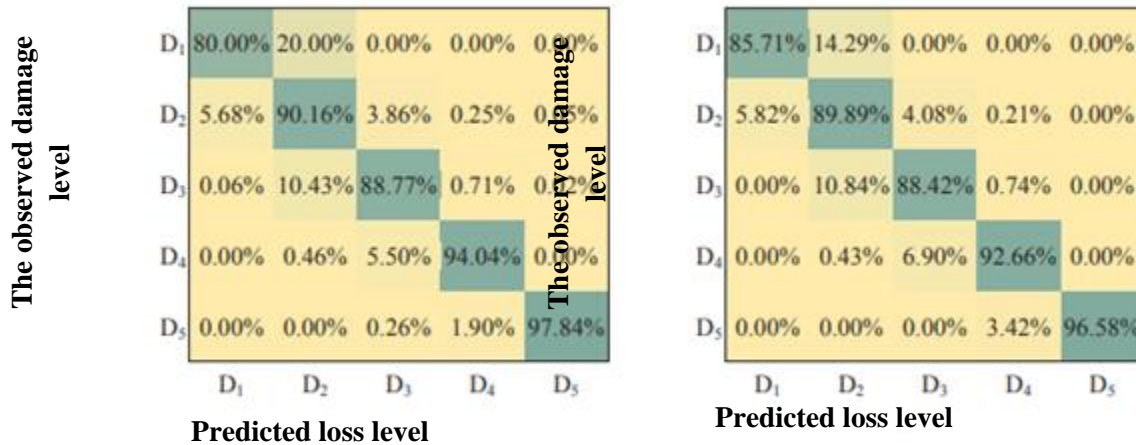


Figure 8. The results from comparing the training and validation stage

Table 5 indicates the comparison between the number of buildings determined in each damage level by observers and by using the fuzzy model for situations of each building. The accuracy of the results shows that this model is consistent with the observers' reports for each situation of the structure. However, slight decrease in the function of buildings R<sub>2</sub>C has been observed that can be due to less number of RC<sub>2</sub> buildings at database.

Table 5. the function of the proposed method for all data

Ty pe	D <sub>1</sub> (none)			D <sub>2</sub> (slight)			D <sub>3</sub> (average)			D <sub>4</sub> (severe)			D <sub>5</sub> (destruction)			The final accu racy
	D <sub>G</sub> abc	D <sub>G</sub> *	(% )	D <sub>G</sub> <sup>a</sup> bc	D <sub>G</sub> <sup>*</sup>	(% )	D <sub>G</sub> abc	D <sub>G</sub> *	(% )	D <sub>G</sub> abc	D <sub>G</sub> *	(% )	D <sub>G</sub> abc	D <sub>G</sub> *	(% )	
RC <sub>1</sub>	62	51	82.26	9823	8431	85.83	2883	2311	80.16	1091	964	88.36	355	347	97.75	86.87
RC <sub>2</sub>	0	0	0	336	292	86.90	182	133	73.08	57	42	73.68	10	8	80	78.42
S	1	1	100	77	71	92.21	37	22	59.46	21	18	85.71	4	4	100	87.48
URM	8	6	75	5522	5400	97.79	3693	3229	69.37	1921	1869	97.29	1288	1288	97.52	92.79
Total	71	58	81.63	15758	14194	90.07	6795	6025	88.67	3067	2893	93.62	1657	1657	97.47	90.30

Moreover, this model can determine the damage level specific to the following:

"Structure body" as a whole, which is proportional to the effect of "structural components". The structural damage D<sub>s</sub><sup>\*</sup> is obtained by using the equation 10 so that the structural components (SC,VC,LC,FR,SR) are determined (table 6).

"Non-structural body" as a whole and proportional to the effect of "secondary or non-structural components". Non-structural damage  $D_{ns}^*$  can be obtained by using equation 10 so that the non-structural components (ST, EW, IC, EC) can be evaluated.

This "body damage" has not been considered in the main assessment form. This new probability at the research method can be considered as the improvement in damage assessment process. Some examples extracted from the databases have been shown in table 6, it can be seen from this table that the general damages are proportional to the proposed damage by the observers and decisions made in many cases.

Table6. Comparison between the theoretical results and the results presented by observers

N°	$d_{SC}$	$d_{VC}$	$d_{LC}$	$d_{FR}$	$d_{SR}$	$D_S^*$	$d_{ST}$	$d_{EW}$	$d_{IC}$	$d_{EC}$	$D_{ns}^*$	$D_G^*$	The model decision	$D_G^{Obs}$	The observer decision
1	/	$d_1$	$d_1$	$d_1$	/	$D_1$	/	$d_2$	$d_2$	/	$D_2$	$D_2$	Safe	$D_2$	Safe
2	/	$d_2$	$d_2$	$d_3$	/	$D_3$	$d_2$	$d_3$	$d_2$	$d_3$	$D_3$	$D_3$	Unsafe	$D_3$	Unsafe
3	/	$d_1$	$d_1$	$d_1$	/	$D_1$	/	$d_1$	$d_2$	/	$D_1$	$D_1$	Safe	$D_1$	Safe
4	/	$d_4$	$d_4$	/	$d_3$	$D_4$	/	$d_3$	$d_3$	/	$D_3$	$D_4$	Unsafe	$D_4$	Unsafe
5	/	$d_2$	$d_2$	$d_2$	$d_2$	$D_2$	/	$d_3$	$d_2$	/	$D_3$	$D_2$	Safe	$D_2$	Safe
6	/	$d_5$	$d_5$	/	$d_5$	$D_5$	/	$d_5$	$d_5$	/	$D_5$	$D_5$	Dangerous	$D_5$	Dangerous
7	$d_2$	$d_1$	$d_1$	$d_1$	/	$D_2$	$d_2$	$d_2$	$d_2$	$d_2$	$D_2$	$D_2$	Safe	$D_2$	Safe
8	/	$d_1$	$d_1$	$d_1$	/	$D_1$	/	$d_1$	$d_1$	/	$D_1$	$D_1$	Safe	$D_1$	Safe
9	/	$d_2$	$d_2$	/	$d_2$	$D_2$	/	$d_3$	$d_2$	/	$D_3$	$D_2$	Safe	$D_3$	Unsafe
10	/	$d_1$	$d_1$	$d_1$	/	$D_1$	$d_1$	$d_2$	$d_2$	/	$D_2$	$D_2$	Safe	$D_2$	Safe
11	/	$d_5$	$d_5$	/	$d_5$	$D_5$	/	$d_5$	$d_5$	/	$D_5$	$D_5$	Dangerous	$D_5$	Dangerous
12	$d_1$	$d_1$	$d_1$	$d_1$	/	$D_1$	$d_1$	$d_3$	$d_2$	/	$D_2$	$D_2$	Safe	$D_2$	Safe
13	/	$d_3$	$d_3$	/	/	$D_3$	$d_4$	$d_3$	$d_3$	$d_1$	$D_3$	$D_3$	Unsafe	$D_3$	Unsafe
14	/	$d_2$	$d_2$	$d_2$	/	$D_2$	$d_1$	$d_2$	$d_3$	/	$D_2$	$D_2$	Safe	$D_3$	Unsafe
15	/	$d_2$	$d_2$	$d_2$	$d_2$	$D_2$	$d_2$	$d_2$	$d_2$	/	$D_2$	$D_2$	Safe	$D_2$	Safe
16	/	$d_1$	$d_1$	$d_1$	/	$D_1$	$d_1$	$d_1$	$d_2$	/	$D_1$	$D_1$	Safe	$D_2$	Safe
17	$d_1$	$d_4$	$d_4$	$d_1$	/	$D_4$	/	$d_4$	$d_4$	/	$D_4$	$D_4$	Unsafe	$D_4$	Unsafe
18	/	$d_1$	$d_1$	$d_2$	/	$D_2$	$d_1$	$d_1$	$d_2$	/	$D_1$	$D_2$	Safe	$D_2$	Safe
19	/	$d_5$	$d_5$	/	$d_5$	$D_5$	/	$d_5$	/	/	$D_5$	$D_5$	Dangerous	$D_5$	Dangerous
20	/	$d_3$	$d_3$	$d_2$	/	$D_3$	$d_3$	$d_4$	$d_4$	$d_4$	$D_3$	$D_3$	Unsafe	$D_4$	Unsafe

dangerous

unsafe

Safe

Finally, using the weighted fuzzy rule is justified according to its simplicity and performance. As mentioned above, the provided model in this research usually needs to  $4181 (= 5^5 + 4^5 + 2^5)$  of fuzzy rule to cover all possibilities traditionally. Since all the compositions are not applicable, reviewing and selecting important rules to reduce their number requires a lot of time and effort. But, less number of rules is determined by using weighted fuzzy rules. This model is made by using 55 rules ( $= 5*5+4*5+2*5$ ) which represents only 1.32% of the number of previous rules. The proposed method can be effectively used in automated process of building assessment methods, because it is a simple and accurate method for making fuzzy systems in which the development and definition of fuzzy sets, data and yield variables, as well as fuzzy rules and their weights are easily determined.

#### Conclusion:

During examining the post-earthquake damages, assessing the damage to the buildings is an important task. Damaged buildings should be assessed quickly and accurately. After great earthquakes, observers always encounter problems in assessing the damaged buildings and providing the general damages accurately, and non-expert observers are presented in this



process and this leads to misclassification of the real extent of damages. To overcome these problems and weaknesses, expertized systems are used to help the monitoring during the assessment. In this study, an automated processing method has been provided that helps observers to provide a better performance in post-earthquake assessment. The proposed method assessed the general damages and also considers incorrect and incomplete information. This method focuses on the observed damage in each "structural components" (pillars, beams, walls, crushes of stones) and "non-structural components" (stairs, partition walls, façade, balcony etc.). The proposed method is based on fuzzy logic and the rules related to the weighted fuzzy, so that the number of fuzzy rules are reduced in it and this implies the development and expansion of fuzzy systems. The weight of fuzzy rule indicates the resistant of the rule and states the relation between the damage of components and the general damage.

The provided method in this research includes "group" in fuzzy systems. The first fuzzy system "group 1" evaluates 5 parameters as structural parameters and determines the damage level of "the structure". The second fuzzy system "group 2" evaluates 4 parameters as non-structural parameters and determines the non-structural damage. Both structural and non-structural damages determined by these systems have not been included in the main form and are used in the post-earthquake process of evaluation assessment. The third fuzzy system "group 1-2" focuses on the "structural" and "non-structural" damages placed in the intervals of  $D_1$  (no damage) to  $D_2$  (destruction). For descriptive purposes, a database of 27,000 building assessment forms was compiled from a post-earthquake survey.

Weights of fuzzy rule are optimized by minimizing the target optimization function. The results indicate that for all the parameters in the first fuzzy system "group 1", the weight of rule goes from  $D_1$  to  $D_5$ . The weights of rules related to the  $D_5$  indicate greater damage and refer to the high gravity in the damage. Moreover, variables have relatively same importance and the damages  $D_3$ ,  $D_2$ ,  $D_1$  have more values for all the "structural" components compared to  $D_1$ ,  $D_2$ . These values have less effect on the general damage. Finally, in the third fuzzy systems "group 1-2", the weights of rule go from  $D_1$  to  $D_5$  for structural and non-structural damages and a significant change has been observed in the value of two input variables. Structural components have the greater effect on the general damage compared to the non-structural components.

In the situation under review, the performance of the proposed method is observed by comparing the theoretical damage level with the real damage level and the compiled database. The results indicate the high performance obtained from the database with 90% accuracy. In this method, the ability to predict the real loss is described in many cases and in relation to the high and low damage level. In addition, the number of fuzzy rules equals to 55 in the used model. The less the number of rules, the less time spent on calculation and development.

In other words, Improvements can always be suggested and be used to improve the performance of the proposed method. More calculation is needed because this method is calculated by using the database based on the assessment method. Therefore, the validation with various databases and different methods of evaluation can confirms the obtained weights that make the relation between the damage of components and the general damage in the building.

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