



## **EXPERT SYSTEM FOR BUILDING DAMAGE EVALUATION IN CASE OF EARTHQUAKE**

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### **SUMMARY**

The building damage assessment is a very important task after a strong earthquake. For taking decisions about the building habitability and reparability it is necessary evaluate the building damage, but the expert professionals are insufficient, and therefore voluntary non-experts professionals must be including in the task. This personnel type displays the tendency to aggravate or to underestimate the real level of damage. This paper develops an expert system for post-earthquake evaluation of building damage, which supports the building damage evaluation by non-experts. It is based on the model considers the damage in structural and architectural elements as well as site seismic effects.

### **POST-EARTHQUAKE DAMAGE EVALUATION**

In case of a strong earthquake, the decision-making on the habitability and reparability of a building is urgent. A bad decision could put human lives in danger. For taking good decisions, the damage evaluation process must be made by a broad group of professionals related to the building construction. It is highly desirable that the people involved in this process have expertise and experience in these tasks. Nevertheless, professionals having these skills in this field are usually only a few and it is necessary to involve inexperienced voluntary engineers or architects. As a consequence, the damage underestimation or overestimation is common. This work proposes the use of the computational intelligence as support to this task and an expert system for the building damage evaluation process, based on artificial neural networks and fuzzy sets.

The development of damage evaluation guidelines for buildings has been necessary in countries with high seismic activity. These guidelines have the aim of taking decisions as soon as possible whether the buildings may continue being used or not. After a strong earthquake, the identification of the constructions which suffered serious damage and that can represent a danger for the community is crucial. The identification of the safe buildings, which can be used as temporary shelters for evacuated people, is also necessary. Some countries have developed systematic guidelines and procedures to evaluate the building damage, like Mexico [1, 2], Japan [3], United States [4], Italy [5], Macedonia [6] (former

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Yugoslavia) and Colombia [7, 8 and 9], among others. Damage evaluations are useful to improve the effectiveness of earthquake-resistant construction codes, by identifying the type of failure in the structural systems.

The number of local professionals that have experience in structural engineering and seismic damage assessment is insufficient when the struck area is extensive. Professionals with little or non-experience must be part of the evaluation teams. According to the findings of risk perception researchers, the tendency of inexpert inspectors is to aggravate or to underestimate the damage level. The information on the damage evaluation is highly subjective and depends on the heuristic and the biases of the inspector in each case. The damage levels always are defined in all evaluation guidelines using linguistic qualifications like light, moderate, severe or strong; these concepts may have different meanings according to the judgement of each person and a defined limit between these assessments does not exist clearly.

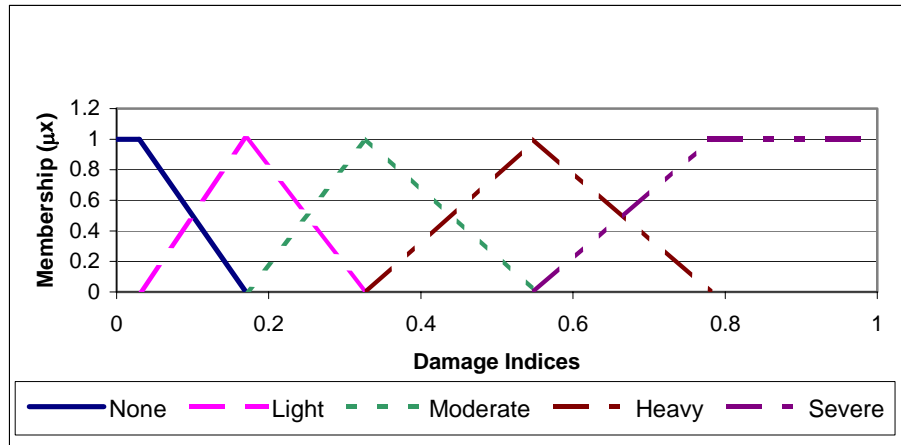
### **COMPUTATIONAL MODEL**

The presented model uses a fuzzy logic approach, required by the subjective and incomplete character of the information. Post-earthquake damage evaluations use qualitative and linguistic expressions that are appropriately handled by the fuzzy sets theory. In addition, an artificial neural network (ANN) is used to calibrate the system using the judgement of specialists. This enables the use of computational intelligence for the damage evaluation by non-experts. Several building damage evaluation guidelines were taken into account in the implementation of this model, as the methodologies used in Mexico, Japan, USA, Italy, Macedonia (old Yugoslavia), the method used after the earthquake of 1999 in the coffee growing area in Colombia [7], and the methods developed for the cities of Bogotá [8] and Manizales [9], Colombia. In addition, members of the Colombian Association for Earthquake Engineering technically supported this work. This model is a user-friendly computer program called Earthquake Damage Evaluation of Buildings, EDE, that was developed using Visual BASIC 6.0. It offers aids for the inspectors, such as detailed descriptions and damage photographs. At present, it is used as official tool by the disaster risk management city offices of Bogotá and Manizales and as a component of the "Program on Building Evaluations after an earthquake", in which new inspection guidelines and forms have been also developed. Recently, another computer program has been developed in California; ATC-20i [10]. That system, unlike this one, does not support the decision making and basically the objective is to facilitate the data collection of the inspection forms of ATC-20.

The artificial neural network (ANN) structure consists of three layers. The neurons in the input layer are grouped in four types, namely structural elements (SE), non-structural elements (NE), ground conditions (GC), and pre-existent conditions (PC). Each one contributes with information to the neurons in the intermediate layer; they only affect the intermediate neuron in the group to which they belong. The input neurons number or variables in the model is not constant; this number depends on the structural system evaluated and on the importance of the different groups of variables for the evaluation. The number of neurons of the input layer used for the structural elements group changes according to the class of building. Table 1 shows the structural elements or variables considered according to the structural system. A qualification is assigned depending on the observed damage using five possible damage levels that are represented by means of fuzzy sets. For structural and non-structural elements, the following linguistics damage qualifications are used: none (N), light (L), moderate (M), heavy (H) and severe (S). Figure 1 illustrates the membership functions for these qualifications. Figures 2 and 3 show some damage levels that can appear in different structural and non-structural elements. The membership functions of fuzzy sets achieve their maximum membership point for the values of the damage indices whose selection will be explained later and is given in Table 3.

**Table 1: Structural elements according to structural system.**

Structural system	Structural elements
RC frames or (with) shear walls	Columns/walls, beams, joints and floors
Steel or wood frames	Columns, beams, connections and floors
Unreinforced/Reinforced/Confined masonry	Bearing walls and floors
Bahareque or tapial walls	Bearing walls and floors



**Figure 1: Membership functions for linguistic qualifications.**



a)



b)

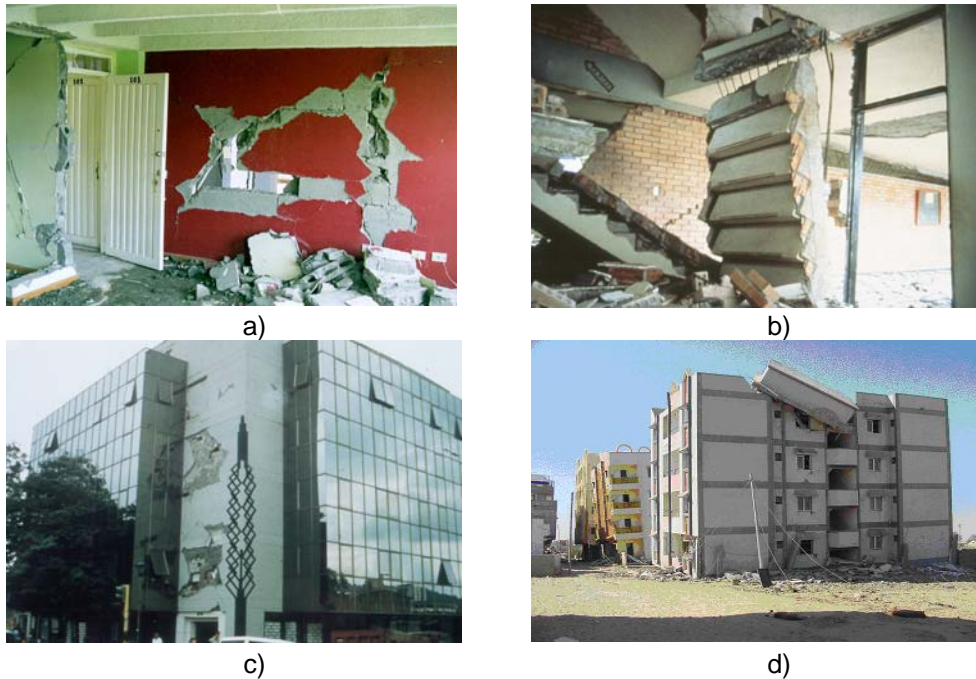


c)



d)

**Figure 2: Damage in structural elements. a) Severe damage in a reinforced concrete joint, b) Moderate damage in a reinforced concrete beam, c) Heavy damage in a masonry wall, d) Heavy damage in an adobe wall.**



**Figure 3: Damage in non-structural elements, a) Severe damage in partitions, b) Severe damage in stairs, c) Moderate damage in elements of façade, d) Severe damage in a tank supported on a building.**

Damage in the non-structural elements does not affect the stability of the buildings, but may put at risk the security of the occupants. The non-structural elements are classified in two groups: elements whose evaluation is compulsory and elements whose evaluation is optional (Table 2).

**Table 2: Non-structural elements.**

Compulsatory evaluation elements	Partitions
	Elements of façade
	Stairs
Optional evaluation elements	Ceiling and lights
	Installations
	Roof
	Elevated tanks

The ground and pre-existent conditions variables are valued through the qualification of their state at the evaluation moment. The linguistic qualifications used are: very good (VG), good (G), medium (M), bad (B), and very bad (VB). Ground conditions consist of variables that can affect the stability of the building, such as landslides and soil liquefaction; examples of these situations can be observed in Figure 4. Pre-existent conditions are related to the quality of the construction materials, plane and vertical shape irregularities of the building, and the structural configuration, illustrated in the Figure 5; these conditions may increase the seismic vulnerability of a building.

In the intermediate layer, an index is obtained by defuzzification for each group of variables. Taking into account the four available indices, it is possible to define in the output layer the building damage using fuzzy rules with the structural and non-structural evaluations. The building habitability is obtained involving also the assessment of the ground conditions. Finally, using the pre-existent conditions, the

system defines the required level of reparation. Thus, habitability and reparability recommendations can be made after an earthquake by using this tool. Remarks as: "habitable after minor adequateness" or "restricted: usable after reparation" or "unsafe: usable after structural strengthening or reinforcement" or "dangerous: possible demolition or total building rehabilitation", are decisions which can be obtained from this expert system.



a)



b)

**Figure 4: Ground conditions, a) Soil settlement and liquefaction, b) Landslides and ground failure.**



a)



b)



c)



d)

**Figure 5: Pre-existent conditions, a) Bad construction quality, b) Vertical shape irregularities, soft floor; c) Plane shape irregularities, d) Bad structural configuration, some elements do not have vertical continuity.**

## DESCRIPTION OF THE ANN

### Input layer of the artificial neural network

The fuzzy sets for each element or variable  $i$  (for instance columns, walls or beams) in the input layer are obtained from the inspector's linguistic qualifications of damage  $D_j$  at each level  $j$  and its extension  $w_j$ . The damage extension, or percentage of each damage level in each element, varies from 0 to 100 and it is normalized

$$w_j = \frac{D_j}{\sum_N D_j}, \sum_N w_j = 1 \quad (1)$$

The accumulated qualification of damage  $D_i$  for each variable is obtained as the union of the scaled fuzzy sets, taking into account the damage membership functions  $\mu_{D_j}(D_j)$ , and its extensions or weights assigned by the inspector

$$D_i = (D_N \cup D_L \cup D_M \cup D_H \cup D_S) \quad (2)$$

$$\mu_{D_i}(D) = \max(w_{N,i} \times \mu_{D_N}(D_{N,i}), \dots, w_{S,i} \times \mu_{D_S}(D_{S,i})) \quad (3)$$

The union in the theory of the fuzzy sets is represented by the maximum membership or dependency. By means of defuzzification, using the centroid of area method (COA), a qualification index  $C_i$  is obtained for each variable of each group of neurons

$$C_i = \left[ \max(w_{N,i} \times \mu_{D_N}(D_{N,i}), \dots, w_{S,i} \times \mu_{D_S}(D_{S,i})) \right]_{centroid} \quad (4)$$

Each variable has predefined the basic membership functions for the fuzzy sets corresponding to the five possible levels of damage. The linguistic qualifications change in each case. Figures 6 and 7 show some examples of the data input of the computer program.

a)

b)

**Figure 6: Input of the damage qualifications. a) Damage extension at each damage level for a structural element, b) For non-structural elements.**



**Figure 7: Input of the qualifications for ground conditions and pre-existent conditions.**  
**a) Landslides and ground failure, b) Structural configuration.**

### Intermediate or hidden layer of ANN

This layer has four neurons corresponding to each group of variables: structural elements, non-structural elements, ground conditions and pre-existent conditions. Figure 8 shows a general scheme of the evaluation process. In this neural network model, the inputs of the four neurons are the qualifications  $C_i$  obtained for each variable of the each group of neurons and its weight  $W_i$  or degree of importance on the corresponding intermediate neuron. These weights were defined with the participation of experts in earthquake damage evaluation. Using these qualifications and weights for each variable  $i$ , a global index could be obtained, for each group  $k$ , from the defuzzification of the union or maximum membership of the scaled fuzzy sets. The membership functions  $\mu_{C_{ki}}(C_{ki})$  and their weights  $W_{ki}$

$$\mu_{CSE}(C) = \max \left( W_{SE1} \times \mu_{C_{SE1}}(C_{SE1}), \dots, W_{SEi} \times \mu_{C_{SEi}}(C_{SEi}) \right) \quad (5)$$

$$I_{SE} = \left[ \max \left( W_{SE1} \times \mu_{C_{SE1}}(C_{SE1}), \dots, W_{SEi} \times \mu_{C_{SEi}}(C_{SEi}) \right) \right]_{centroid} \quad (6)$$

show the notation for the group of structural elements. The groups of variables related to ground and pre-existing conditions are optional, thus they can be or cannot be considered within the evaluation. If this happens, the habitability and reparability of building is assessed only with the structural and non-structural information.

### Output layer of ANN

In this layer, the global indices obtained for structural elements, non-structural elements, ground and pre-existent conditions correspond to one final linguistic qualification in each case. The damage level (qualitative) is obtained according to the "proximity" of the value obtained to a global damage function of reference. In this layer, the training process of the neural network is performed. The indices that identify each qualitative level (center of cluster) are changed in agreement with the indices calculated in each evaluation and with a learning rate. Once the final qualifications are made, it is possible to determine the global building damage, the habitability and reparability of the building using a set of fuzzy rules bases.

## TRAINING PROCESS OF THE ANN

The neuronal network is calibrated in the output layer when the damage functions are defined in relation to the damage matrix indices. In order to start the calibration, a departure point is defined, that means the initial indices of each level of damage. The indices proposed by the ATC-13 [11], Park, Ang and Wen [12], the fragility curves used by HAZUS-99 [13], and the indices used by Sanchez-Silva [14] have been

considered. The values of these indices correspond to the center of area for every membership function related to each damage level. Table 3 shows the indices proposed in this work and the indices proposed by Park [12] and Sanchez-Silva [14] with the aim of comparison. The selection of the initial indices is based on the indices of Park; this choice can be justified on the basis that they have been calibrated with information of several studies.

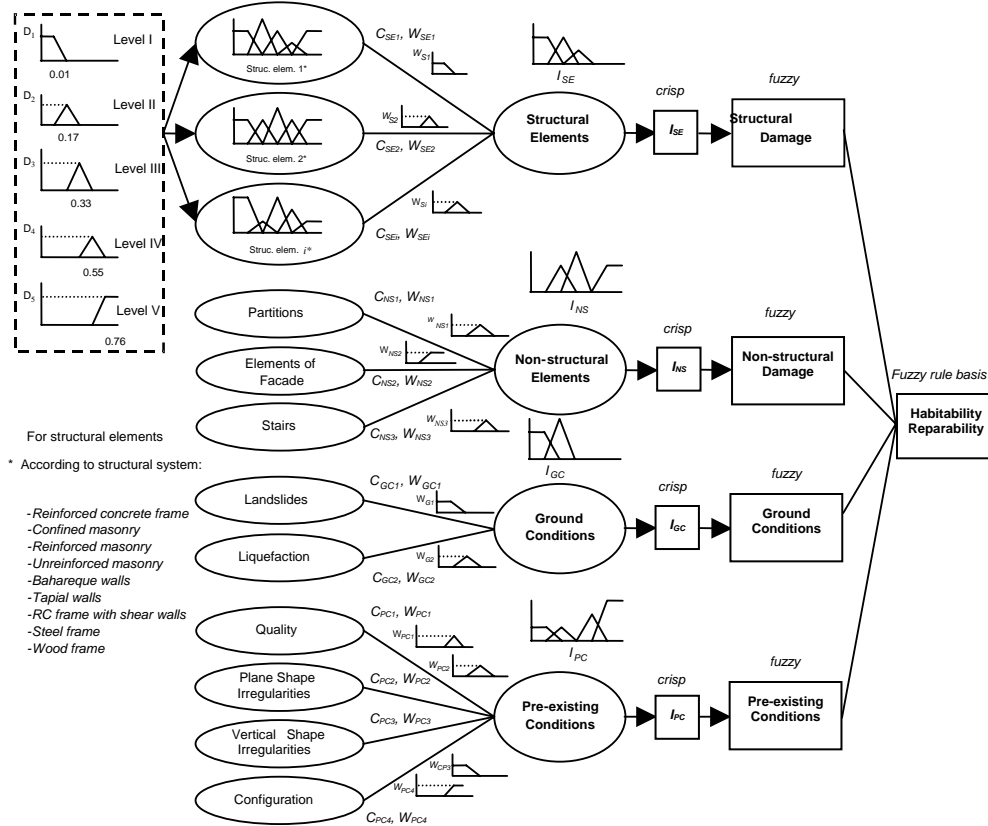


Figure 8: Structure of the proposed artificial neural network.

Table 3: Comparative table for damage indices.

Damage Level	Park, Ang and Wen	Sanchez-Silva	Proposed
Very light	< 0.1 0.07	0.10	0.07
Light	0.10 – 0.25 0.175	0.20	0.17
Moderate	0.25 – 0.40 0.325	0.35	0.33
Severe	0.40 – 0.80 0.6	0.60	0.55
Destruction	>0.80 0.8	0.90	0.76

Some authors consider that collapse occurs for a value equal to 0.8, although Stone [15] propose a collapse threshold of 0.77. According to this opinion, a value of 0.76 has been selected to describe the



destruction level index or collapse. In the selection of the damage index, the authors decided to be conservative, since the indices corresponding to severe and moderate damage have been highly discussed, and doubts exist on whether they should be smaller.

The calibration is performed for each damage level and only the indices corresponding to the groups of variables considered in each evaluation are calibrated. The network learning is made using a Kohonen network

$$I_{kj}(t+1) = I_{kj}(t) + \alpha(t) [I_{kj}(t) - I_{kj}] \quad (7)$$

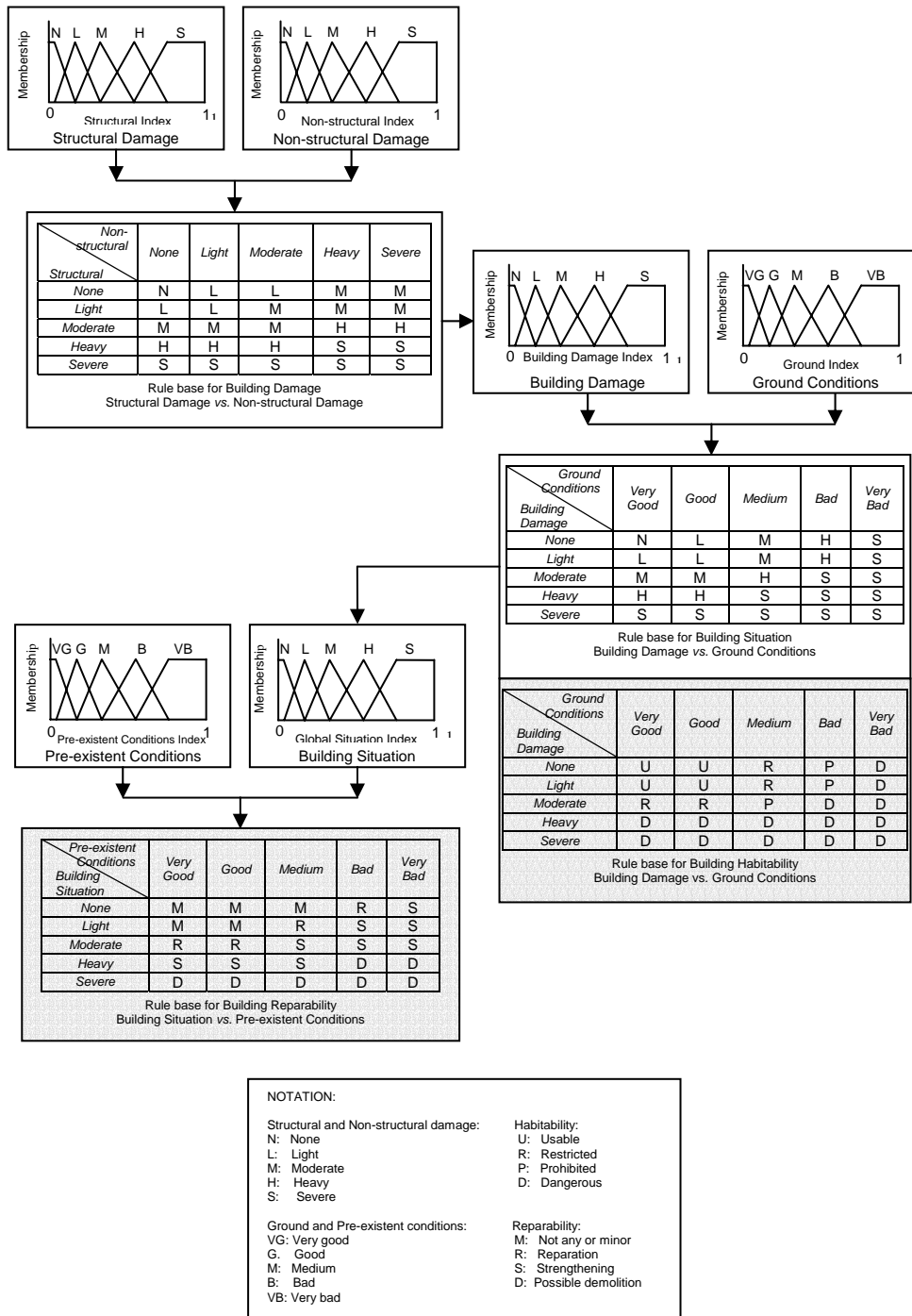
where  $I_{kj}$  is the value of the index of the variables group  $k$  recalculated considering a learning rate  $\alpha$ , a function with exponential decay, and the difference between the resulting index of the present evaluation and the previous indices in each damage level  $j$ . The learning rate is defined by

$$\alpha(t) = 0.1 \times \exp(-0.1 \times t) \quad (8)$$

where  $t$  is the number of times that has been used the index that is calibrated. For training, the damage evaluations made after the Quindío earthquake in Colombia (1999) were used. The neural network has been calibrated for reinforced concrete framed buildings, however more information is necessary to complete the network training for other structural classes, such as wood and steel frame structures, because these building classes are not common in that area. Reinforced concrete frames with shear walls are also only a few, therefore the number of building evaluations to calibrate this structural system were insufficient.

### **FUZZY RULE BASES FOR DECISION-MAKING**

The building habitability and reparability are assessed based on previous results of damage level of the structural and non-structural elements, the state of the ground and pre-existent conditions. Figure 9 displays the fuzzy rule bases used. The global level of a building damage is estimated with the structural and non-structural damage results. This has five possible qualifications: none, light, moderate, heavy and severe damage. The global building state is determined taking into account the rule bases on ground conditions, and by this way the habitability of the building. The linguistic qualification for the building habitability has four possibilities: usable, restricted use, dangerous and prohibited. They mean habitable immediately, usable after reparation, usable after structural reinforcement, and not usable at all. The building reparability depends besides on other fuzzy rule bases: the pre-existent conditions. The building reparability has also four possibilities: not any or minor treatment, reparation, reinforcement, and possible demolition. Figure 10 shows the way in which the results on the state of the building are presented by the computer program developed for the described model.



**Figure 9: Method for building habitability and reparability.**

**EDE RESULTADOS**

Resultados Estado Habitabilidad Reparabilidad

**Daño**

Daño Estructural	Fuerte	0.55
Daño No Estructural	Moderado	0.3614
Condiciones del Suelo	Malas	0.55
Condiciones Preexistentes	Muy Buenas	0.0541

**Riesgo**

Riesgo Estructural	Alto
Riesgo No Estructural	Bajo, después de medidas
Riesgo Geotécnico	Alto

Continuar >>

Guardar Información Aceptar

a)

**EDE RESULTADOS**

Resultados Estado Habitabilidad Reparabilidad

**Daño en el edificio** **Severo**

El edificio ha sufrido daños fuertes en su estructura y daños moderados en sus elementos no estructurales. Por lo tanto, su estabilidad y seguridad están seriamente comprometidas. La capacidad sísmorresistente se encuentra significativamente disminuida.

**Estado global** **Muy Grave**

El edificio presenta daños severos y las condiciones del suelo son malas por lo que la situación del edificio es muy grave.

<< Devolver Continuar >>

Guardar Información Aceptar

b)

**EDE RESULTADOS**

Resultados Estado Habitabilidad Reparabilidad

**Habitabilidad del edificio** **No Habitabile**

**Habitabilidad**

La ocupación de la edificación debe prohibirse porque presenta peligro para la seguridad de los ocupantes debido al muy grave estado del edificio y las graves condiciones del suelo.

**Medidas de seguridad**

Es necesario remover o anclar elementos que están en peligro de caerse y tomar medidas preventivas debido a los graves problemas geotécnicos que se presentan.

<< Devolver Continuar >>

Guardar Información Aceptar

c)

**EDE RESULTADOS**

Resultados Estado Habitabilidad Reparabilidad

**Reparabilidad del edificio** **Posible Demolición**

**Reparaciones**

El edificio posiblemente deberá ser demolido debido a su muy grave estado.

<< Devolver

Guardar Información Aceptar

d)

Figure 10: Results provided by the EDE program.

## CONCLUSIONS

- Starting from a review of different existing guidelines for post-earthquake building damage evaluation, and a review of possible post-earthquake conditions, the authors propose a support tool based on an innovative expert system. The distinct advantages and disadvantages of each method were considered for its development.
- The system was developed by using computational intelligence tools such as artificial neural networks and fuzzy logic approach. These techniques improve the existing field methodologies extending their use to inexpert professionals. This type of tool is very appropriate in the practice, due to the subjective nature of the building damage evaluations and the incomplete information.
- The training of the system was performed by using the database corresponding to the real evaluations made by expert engineers after the earthquake of Quindío (Colombia, 1999).
- The use of AI tools in Civil Engineering has very little diffusion until present, thus it is recommended to promote their use to provide suitable and versatile solutions to different problems in this field of knowledge.

## ACKNOWLEDGEMENTS

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## REFERENCES

1. Rodríguez, M. y Castrillón, E., Instituto Nacional de Ingeniería UNAM - Manual de Evaluación Postsísmica de la Seguridad Estructural de Edificaciones. Basado en investigaciones Realizadas para el Departamento del Distrito Federal. Series del Instituto de Ingeniería 569, 1995
2. Sociedad Mexicana de Ingeniería Sísmica. A.C. Secretaria de Obras y Servicios Gobierno del Distrito Federal. - Manual de Evaluación Postsísmica de la Seguridad Estructural de Edificaciones, 1998
3. Centro Nacional de Prevención de Desastres (CENAPRED). Norma para la Evaluación del Nivel de Daño por Sismo en Estructuras y Guía Técnica de Rehabilitación (Estructuras de Concreto Reforzado). Cuadernos de Investigación, Número 37, México, 1996
4. Applied Technology Council, - Procedures for postearthquake safety evaluation of buildings, ATC-20, Redwood City, CA, 1989
5. Goretti A., Post-earthquake building usability: a Assessment. Technical Report SSN/RT/01/03, 2001.
6. Instituto de Ingeniería Sísmica y Sismología –IZIIS - Metodología y Procedimiento para la Evaluación de Daños Producidos por Terremotos. Universidad “Kiril y Metodij” – Skopje, Yugoslavia, 1984.
7. Campos, A. - Memoria Técnica del Censo de Inmuebles Afectados por el Sismo del 25 de Enero de 1999 en El Eje Cafetero, Ministerio de Desarrollo Económico, Bogotá D.C., Colombia, 1999
8. AIS, Asociación Colombiana de Ingeniería Sísmica, - Guía Técnica para Inspección de Edificaciones Después de un Sísmo. Manual de Campo, Bogotá, D.C., Colombia, 2002
9. AIS, Asociación Colombiana de Ingeniería Sísmica, Manual de Campo para Inspección de Edificios Después de un Sísmo. Manizales, Colombia, 2003
10. Applied Technology Council, Users manual: Mobile postearthquake building safety evaluation data acquisition system (Version 1.0), ATC-20i. Redwood City, California, 2003.
11. Applied Technology Council, Earthquake damage evaluation data for California, ATC-13, Redwood City, CA, 1985
12. Park Y.J., Ang A. and Wen Y., Seismic Damage Analysis and Damage-Limiting Design of R.C. Buildings. Structural Research Series, Report No 516, University of Illinois at Urban-Champaign, Urbana, 1984
13. FEMA, Federal Emergency Management Agency, Earthquake Loss Estimation Methodology HAZUS, Technical Manual, Vol. I, II and III, First edition 1997, National Institute of Buildings Sciences of Federal Emergency Management Agency, Washington, 1999
14. Sanchez-Silva, M. and García, L. Earthquake Damage Assessment Based on Fuzzy Logic and Neural Networks. EERI Earthquake Spectra, Vol. 17, N. 1, February, pp. 89-112. Oakland, California, 2001.
15. Stone, W.C., Taylor, A.W, Seismic Performance of Circular Bridge Columns Designed in Accordance with AASHTO/CALTRANS standards, NIST Building Science Series 170, National Institute of Standards and Technology, Gaithersburg MD, 1993.