

Chapter VII

Neuro-Fuzzy Assessment of Building Damage and Safety After an Earthquake

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Abstract

This chapter describes the algorithmic basis of a computational intelligence technique, based on a neuro-fuzzy system, developed with the objective of assisting nonexpert professionals of building construction to evaluate the damage and safety of buildings after strong earthquakes, facilitating decision-making during the emergency response phase on their habitability and reparability. A hybrid neuro-fuzzy system is proposed, based on a special three-layer feedforward artificial neural network and fuzzy rule bases. The inputs to the system are fuzzy sets, taking into account that the damage levels of the structural components are linguistic variables, defined by means of qualifications such as slight, moderate or severe, which are very appropriate to handle subjective and incomplete information. The chapter is a contribution to the understanding of how soft computing applications, such as artificial neural networks and fuzzy sets, can be used to complex and urgent processes of engineering decision-making, like the building occupancy after a seismic disaster.

Introduction

After an earthquake, it is necessary to answer some urgent questions, such as: How many buildings were affected? What is the geographic distribution of damage? What was the degree of damage? Are the buildings habitable, and what is the level of safety? Must people be evacuated? What type of alternative actions should be immediately taken? Are there trapped people? What structures represent danger for neighbours and pedestrians? What types of buildings were affected? In order to answer all these questions, it is necessary to carry out an accurate process of damage evaluation that requires the participation of professional experts in the field. Unfortunately, the number of professionals who fulfil that expertise is always insufficient and, therefore, the evaluation process becomes even more difficult. By one hand, for nonexperts, the impact caused by seeing damage is so great that they tend to describe it as more severe than it really is. By the other hand, non experts can underestimate cases of severe damage because of their innocuous appearance. There is no doubt that the information obtained during the evaluation process is highly subjective and that it depends on the conception and the impression that the inspectors have about each case. In all evaluation methods, the damage levels are defined with linguistic qualifications such as light, minor, moderate, average, severe, etc. These definitions can have a remarkable variation in their meaning according to the person who uses them.

Soft computing can be used to overcome these difficulties of damage evaluation. Neural networks have been used to face complex problems simulating the function of the human neural system, imitating the adaptive and cognitive mechanisms of human learning. Fuzzy logic is an innovative way of representing qualitative or subjective information in numerical form, very useful for technologic and engineering applications where expert criteria are required. Referring to risk evaluation, Carreño, Cardona, and Barbat (2004) and Cardona (2005), applied soft computing techniques to make evaluations of urban seismic risk before and after earthquakes (*ex-ante* and *ex-post* evaluations) and to measure the disaster risk management performance and effectiveness at national, subnational and local level). Considering these features and applications of the computational intelligence techniques and the decision-making needed to determine the habitability and reparability of affected buildings after a seismic disaster, an expert system for post-earthquake building damage and safety evaluation, using a nonsupervised learning Kohonen neuro-fuzzy algorithm, was designed to avoid the mistakes usually made by nonexpert building inspectors when handling subjective and incomplete information. This model considers the possibility of damage in structural and architectural elements and the potential site seismic effects. It also takes into account the preexisting conditions that increase the building vulnerability, such as the bad quality of the construction materials.

Postearthquake Building Damage Evaluation

Seismic Damage of Buildings

After a strong earthquake strikes a vulnerable urban centre, too much damage may occur on the exposed elements like buildings, facilities, and infrastructure lifelines. The damaged buildings could be many and scattered in the city and the damage degrees could be several. The population and governmental officials usually become very concerned about the security of their lives and they need to know if their buildings are safe or not. This question only can be answered by engineers and architects experts in structural and soil mechanics, damage evaluation and building rehabilitation. The decision-making on the habitability and reparability of buildings is urgent; a bad decision could jeopardize human lives.

The damage evaluation is a difficult task and its results depend on the experience of the inspector. Sometimes, a building is obviously unsafe due to the observed damage (see Figures 1-4), but the most cases can generate doubts (see Figures 5-7). In the diagnostic of a building, it is necessary to take into account not only the different damage levels of the elements, but also the overall structural stability. Affected structural and non structural elements can endanger the human life in different ways. The damage of a building can be isolated or generalised and, in both cases, can put in danger the structural stability, depending on the structural configuration or redundancy and on the adverse ground conditions.

The state-of-the-art of earthquakes and seismic damage of buildings have allowed the development of appropriate earthquake resistant design and construction techniques. These techniques include technical and economical criteria to obtain less strong but more ductile structures permitting to control damage without collapse by dissipating a part of the absorbed seismic energy. In general, the building seismic codes accept heavy damage without collapse of the building in case of severe earthquakes; nonstructural effects without or with minor structural damage in case of moderate earthquakes; and slight or no damage when moderate earthquakes occur (Cardona, 2001).

Dowrick (1987) says that a structure will have the maximum chance of surviving an earthquake if the following are true:

- The load-bearing members are uniformly distributed.
- The columns and walls are continuous and without offsets from roof to foundation.
- All beams are free form offsets.
- Columns and beams are co-axial.
- Reinforced concrete columns and beams have nearly the same width.
- Nonprincipal members does not change sections suddenly.
- The structure is a continuous, redundant, and as monolithic as possible.

The ductility and structural redundancy have been the criteria more effective to assure the security against the structural collapse (García, 1998). In reinforced concrete buildings,

Figure 5. Affected bus terminal in Colombia (1983)

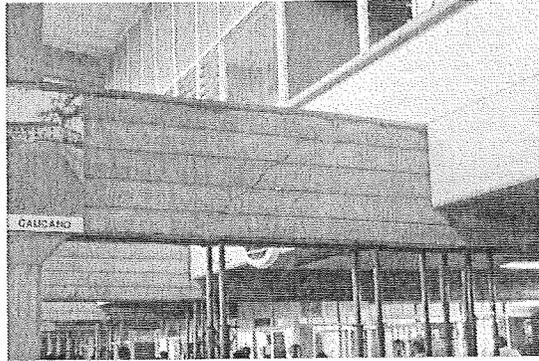


Figure 6. Damaged column in a residential building in Colombia (1999)

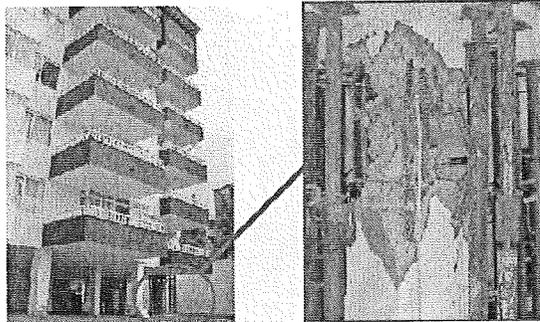


Figure 7. Cracked beam in a office building in Colombia (1999)

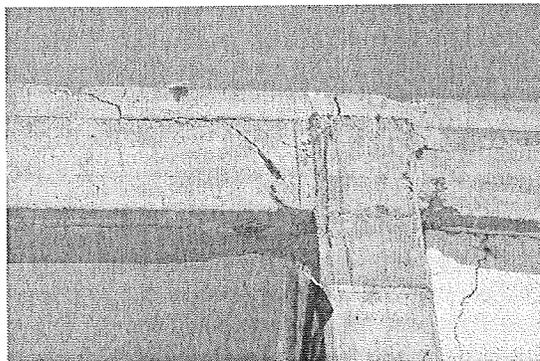
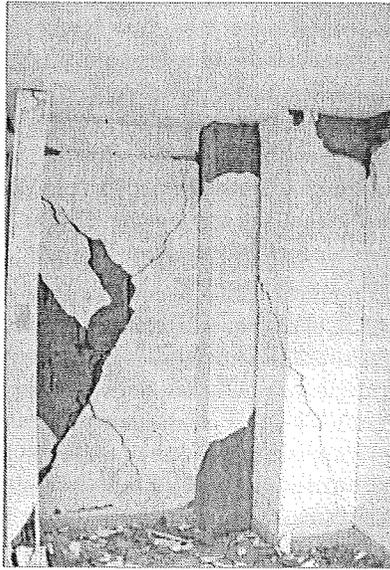


Figure 8. Cracks in fragile masonry walls



Existing Seismic Damage Evaluation Methodologies and Guidelines

When the seismic damage is extended and widespread, the number of the required professionals with the experience to tackle the damage assessment is always insufficient. All massive evaluation processes depart from the need to involve voluntary professionals without expertise and experience to determine the habitability and reparability of many buildings; decision-making is really difficult for the nonexpert professionals. The need of avoiding unnecessary demolitions and of helping to define accurate and cost-effective measures of repairing or reinforcing the damaged buildings are the main objectives of the existing damage evaluation methodologies and guidelines.

The development of damage evaluation guidelines has been necessary in countries with high seismic activity. These guidelines have the aim of defining, as soon as possible, whether the buildings may continue being used or not, and identifying safe buildings which can be used as temporary shelters for the evacuated persons. In addition, damage evaluations are essential to make decisions not only about the structural safety, but also to improve the effective earthquake-resistant construction codes by identifying the types of failures of the different structural systems. Using the data of building damage, it is also possible to develop empirical vulnerability functions which are useful to classify and study the affected buildings.

Some countries have developed systematic guidelines and procedures to evaluate the building damage. The main efforts, described by Carreño, Cardona, and Barbat (2005), are the following:

After the Skopje's earthquake of 1963, and particularly after the Montenegro earthquake of 1979, the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) of the University "Kiril and Metodij" of the Former Yugoslav Republic of Macedonia, developed a methodology for the damage evaluation after an earthquake (Instituto de Ingeniería Sísmica y Sismología [IZIIS], 1984). Its main objectives were the reduction of human losses in buildings with low resistance or in damaged buildings which could be destroyed by aftershocks; data acquisition regarding the magnitude of a disaster in terms of available housing, destroyed buildings and unsafe buildings; data acquisition for civil protection and rescue planning and organization after earthquakes; and the improvement of the design specifications of the earthquake resistant construction codes. This methodology and procedure was translated to Spanish and used after the Mexico earthquake of 1985.

Applied Technology Council (ATC; 1989) proposed for California and, in general, for United States the "Procedures for post-earthquake safety evaluation of buildings" (ATC, 1989, p. 20) with three steps. The first one is the rapid evaluation, in which it is decided if a building is obviously unsafe or apparently habitable. These evaluations are often cursory, because there is no sufficient personnel available to perform more thorough inspections. The second step corresponds to the detailed evaluation, in which the buildings obviously unsafe are visually evaluated by a structural engineer. The third step is the engineering evaluation, which is performed for questionable and severely damaged buildings that have to be rehabilitated by the owner's engineer. A second version of the procedure was published in 1995 with the title *Addendum to the ATC 20 Postearthquake Building Safety Evaluation Procedures* (ATC, 1989, pp. 20-22). In 2003, a mobile postearthquake building safety evaluation data acquisition system was developed—ATC 20i (ATC, 2003), and in 2005, the second edition of the ATC 20-1 *Field Manual: Postearthquake Safety Evaluation of Buildings*, (ATC, 2005) was published.

After the Miyagiken-Oki earthquake, in 1978, the *Guides for Damage Evaluation After an Earthquake and Restore Techniques* were published and tested after the Nihonkai-Chumbu earthquake in 1983 and after the Mexico earthquake in 1985. The methodology was reviewed in 1989 and was published by the Japanese Association for the Disaster Prevention in Buildings (CENAPRED, 1996). Accordingly, the buildings which have to be evaluated are selected by a general inspection after the earthquake. The evaluation is performed in two steps: an immediate visual evaluation of risk level or habitability and a visual evaluation of the degree of structural damage. The first step establishes if the damaged structure or a part of it puts in danger the human life by overturning, failure or collapse. In the second step, the evaluation is based on the level of damage of the building and its components. As a result of this process, a suggestion is made to the owner regarding the necessity of structural rehabilitation (repair, reinforcement, or demolition).

In Mexico, the Institute of Engineering of the National University (UNAM) developed the *Guideline for Post-Earthquake Evaluation of the Structural Safety of Buildings* (Rodríguez & Castrillón, 1995). This method was reviewed and published by the Mexican Society for Earthquake Engineering (Sociedad Mexicana de Ingeniería Sísmica; SMIS) and the government of Mexico City in 1998 (SMIS, 1998) and, like the ATC 20, has three steps: a rapid evaluation, a detailed evaluation and a specialized engineering evaluation..

After the earthquake of Friuli in 1976, in Italy was developed a procedure for estimating the economic losses. More recently, a proposal was published by Goretti (2001) based on

a research programme started in 1995. Guidelines and forms were published in 2000 after the earthquakes of Umbria-Marche in 1997 and Pollino in 1998, where the major part of the published decrees for evacuation or limited use of buildings were in agreement with the suggestions made by the inspectors. Another important initiative has been the development of the self-training multimedia tool called MEDEA (Manuale di Esercitazioni sul Danno Ed Agibilità) promoted by the Servizio Sismico Nazionale (Papa & Zuccaro, 2003; Zuccaro & Papa, 2002), which was proposed as a handbook for a consistent classification of the structural elements of masonry and reinforced concrete buildings and of their relevant damage typologies.

In Colombia, evaluation methodologies for some important cities have been developed and later have been reviewed using actual damage data. After the coffee-growing-area earthquake of 1999, several studies have been made in Colombia on seismic hazard and vulnerability to promote seismic risk reduction of buildings and infrastructure (Campos, 1999). In one of the most important projects, lead by the Colombian Association for Earthquake Engineering (Asociación Colombiana de Ingeniería Sísmica; AIS), a methodology for habitability and reparability evaluation of buildings in case of earthquakes has been developed. This method was adopted officially by cities like Bogotá (AIS, 2002) and Manizales (AIS, 2003) and includes an evaluation form, a field manual for the evaluation of the damaged buildings and a neuro-fuzzy system used in the habitability and reparability evaluation (AIS, 2004), which is described in this chapter.

Other works are related to the detection of damaged building in disaster areas using satellite images. One of them is the method proposed by Matsuoka and Yamazaki (2004), which uses satellite synthetic aperture radar (SAR) to identify the distribution of the damaged buildings in the area after a disaster by comparing the pre- and postevent images. This tool helps to detect the extension and magnitude of disasters and is useful for disaster management activities.

Common Problems of Damage and Habitability Evaluations

Taking into account the experiences acquired during different earthquakes and, particularly, the lessons learned in California in 1989 and 1994 about the application of the ATC 20, and after the earthquakes of Colombia occurred in 1995 and 1999, it is possible to say that the damage evaluation processes presents similar problems and difficulties in different countries. The most important shortcomings are the following:

- **The lack of training and qualification of inspectors:** According to the findings of risk perception researchers, the tendency of nonexpert inspectors is to aggravate or to underestimate the damage level of buildings. The information obtained during the damage evaluation process is highly subjective and depends on the inspector's heuristic and biases. For this reason, it is desirable the previous identification and training of inspectors and the anticipated organization of the evaluation activities.
- **Subjectivity of the evaluation:** The damage levels in all methodologies and evaluation guidelines are defined using linguistic qualifications like light, moderate or se-

vere; which may have different meanings according to the judgement of each person. Moreover, the limit between these assessments is not clear. This is the reason why it is necessary to improve the standardisation of the meaning of damage levels before any evaluation.

- **Building location problems:** Other difficulty is the lack of standardisation of the postal addresses in certain cities; this makes difficult the visits of the professional teams, the organisation of the obtained data and the development of maps of damage. One suggestion made after several disasters, was to cover the total number of affected buildings to avoid confusion and misunderstanding of people. In addition, inspectors should have clear guidelines to provide appropriate information about damage to the owners due to the fact that, in some cases, bad communications can exacerbate legal problems and government liabilities.
- **The lack of data organization and systematization:** It is important to have official records of every action and decision; bad quality data and lack of systematization contribute to the confusion and to delay relevant decisions from the perspective of disaster management. On the other hand, it is necessary to have in advance a contingency plan in which the damage evaluation process is one of the needed tasks in order to avoid coordination difficulties among all the governmental emergency agencies, from the local and regional to the national level.

Application of Neural Networks and Fuzzy Sets to Damage Assessment

As mention above, the lack of experience of the inspectors and the unavoidable need of involving in the process nonexpert professionals, make very difficult the decision making regarding safety of the affected buildings. Techniques of computational intelligence facilitate the massive and correct evaluation of damage, risk, habitability and reparability of the state of the affected buildings after an earthquake. Taking into account the different perspectives in using these techniques and tools, some basic definitions are useful to understand their applications:

- **Neural networks:** They are systems that make use of the known or expected organizing principles of the human brain. They consist of a number of independent and simple processors: the neurons. These neurons communicate with each other via weighted connections, the synaptic weights (Nauck, Klawonn, & Kruse, 1997).
- **Linguistic variable:** This concept was introduced by Zadeh (1975) to provide a basis for approximated reasoning, as follows: "By a linguistic variable we mean a variable whose values are words or sentences in a natural or artificial language. The motivation for the use of words or sentences rather than numbers is that linguistic characterizations are, in general, less specific than numerical ones" (Rutkowska, 2002).
- **Fuzzy set:** It is a set without a crisp boundary. The transition from "belong to a set" to "not belong to a set" is gradual and this smooth transition is characterised by members.

The imprecisely defined sets play an important role in human thinking, particularly in the domains of pattern recognition, communication of information and abstraction (Zadeh, 1965). Some authors proposed extend the learning methods to fuzzy training application using fuzzy partial matching indices (Cross & Sudkamp, 1991; Dubois & Prade, 1982) to determine the degree of match. Another approach to learning fuzzy rules has been proposed by Kosko (1992). Kosko envisages the construction of a rule base as a search through the space of all fuzzy rule bases over a fixed topology.

- **Soft computing:** It is an emerging approach to computing which parallels the remarkable ability of the human mind to reason and learn in an environment of uncertainty and imprecision (Zadeh, 1992). The principal constituents of soft computing are fuzzy logic, neurocomputing and genetic algorithms. According to Jang, Sun and Mizutani (1997), human expertise, biologically inspired computing models, new optimization techniques, numerical computation, new application domains, model-free learning, intensive computation, fault tolerance, goal driven characteristics, real-world applications, are the main characteristics of soft computing.
- **Approximate reasoning:** Reasoning with fuzzy logic is not exact but rather is approximate. Based on fuzzy premises and fuzzy implications, fuzzy conclusions are inferred (Rutkowska, 2002).
- **Neuro-fuzzy system:** It is a combination of neural networks and fuzzy systems in such a way that neural networks, or neural networks learning algorithms, are used to determine parameters of fuzzy systems (Nauck et al., 1997).

In the framework of the damage evaluation Chou and Ghaboussi (2001) studied the application of genetic algorithms to damage detection. Static measures of displacements are used to identify the changes of the properties of structural members, such as Young's modulus and the cross-sectional area. For this implementation, bridges have been instrumented and remotely monitored. The earthquake damage evolution was studied by Song, Hao, Murakami, and Sadohara (1996) using fuzzy theory. Zhao and Chen (2002) proposed a fuzzy system for concrete bridge damage diagnosis. They built the membership functions of the input variables with a fuzzy partitioning algorithm and induced the fuzzy rules from the numerical data. The diagnosis is based on three kinds of factors: design factors, like structural type, span length, deck width, number of spans, etc.; environmental factors, like humidity and precipitation, climate of the region, traffic volume, temperature variations, and so forth; and other factors, like the structure age, function class and location of damages. Lagaros, Papadrakakis, Fragiadakis, Stefanou, and Tsompanakis (2005) proposed the application of artificial neural networks for the probabilistic safety analysis of structural systems under seismic loading. Ahlawat and Ramaswamy (2001) proposed a system for structural vibration control using the fuzzy sets theory.

The soft computing tools have been used in solving problems in many other areas in the field of earthquake engineering. Other two works related to structural behaviour are the application of neural networks in the stochastic mechanics (Hurtado, 2001) or the estimation of the service life of reinforced concrete structural members using fuzzy sets (Anoop, Rao, & Rao, 2002).

Proposed Soft Computing Model

Expert System for Damage Evaluation

In spite of the benefits of the damage evaluation methodologies and guidelines for buildings discussed in the previous section, decision mistakes like demolition of noncritical buildings or unnecessary building evacuation are still possible due to the lack of experience and qualification of inspectors. This represents serious burdens, especially in the case of key buildings. On the other hand, it is possible that building damages that put at risk the structural stability could be ignored, jeopardizing the life of the occupants. This is the reason why a neuro-fuzzy expert system and a computational model have been proposed and designed to be used in the emergency response phase in case of strong earthquakes (Carreño, Cardona, & Barbat, 2003).

This section describes the use of the soft computing as support to the building habitability evaluation. The expert system for the building damage evaluation process is based on artificial neural networks and fuzzy sets. The authors have been working in this model since 2000 and, although this tool has not been tested yet in a real earthquake emergency, recently it has been adopted officially by the administrations of the cities of Bogotá and Manizales, in Colombia, to face future earthquakes and complement its calibration, once the calibration performed, the system will be ready for use in a real case of earthquake emergency. The model uses a fuzzy logic approach, required by the subjective available information which can be based on linguistic qualifications for the damage levels and can be incomplete. This enables the use of computational intelligence for the damage evaluation by nonexperts.

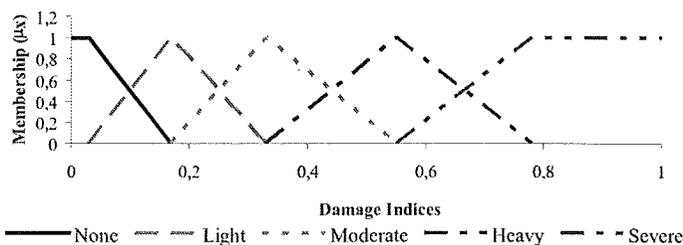
For the building evaluation four groups of elements were identified: structural elements, non structural elements, ground conditions and preexisting conditions. The first three indicate the damage condition of the building that can jeopardize the life of the occupants. Preexistent conditions are related to the quality of the construction materials, plane and vertical shape irregularities of the building, and the structural configuration and help to identify the building reparability condition.

The proposed model uses an artificial neural network (ANN). Its structure consists of three layers. The neurons in the input layer are grouped in four sets, namely structural elements (SE), nonstructural elements (NE), ground conditions (GC) and preexistent 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 number of input neurons or variables in the model is not constant; this number varies depending on the structural system and on the importance of the groups of variables for the evaluation. In some cases, it is not necessary to evaluate the ground conditions or the preexistent conditions if the damage is important. The number of neurons of the input layer used to analyse the state of 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 nonstructural elements, the following linguistics damage state qualifications are used: none (N), light (L), moderate (M), heavy (H) and severe (S). Figure 9 illustrates the membership functions for these qualifications.

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 9. Membership functions for linguistic qualifications



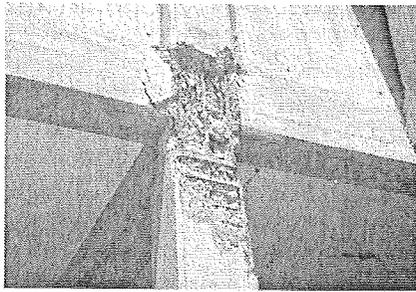
The damage levels in different structural and nonstructural elements of buildings having different typologies can be seen in Figures 10 and 11. The membership functions of the fuzzy sets reach their maximum membership point for the values of the damage indices whose selection will be explained later and is given in Table 3.

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

The ground and preexistent conditions variables are valued through the qualification of their state in the evaluation moment. The used linguistic qualifications are: very good (VG), medium or poor (M), 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 12. Preexistent conditions are illustrated in Figure 13 and can 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 nonstructural evaluations. The concept of linguistic variable was a stepping-stone to the concept of a fuzzy IF-THEN rule. Fuzzy rules and their manipulation refer to the so-called calculation of fuzzy rules, the largely self-contained part of fuzzy logic often used in practical applications (Rutkowska, 2002; Zadeh, 1975, 1996). The concept of fuzzy rule is important when the dependencies described by these rules are imprecise or a high degree of precision is not required (Rut-

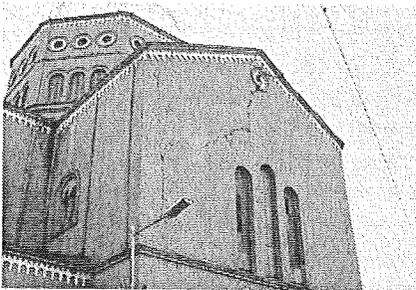
Figure 10. Damage in structural elements: (a) Severe damage in a reinforced concrete joint, (b) moderate damage in a reinforced concrete beam, (c) heavy damage in a masonry wall, (d) heavy damage in a bahareque wall



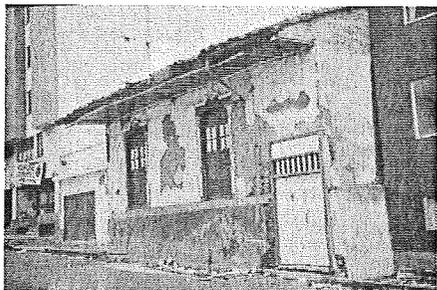
(a)



(b)

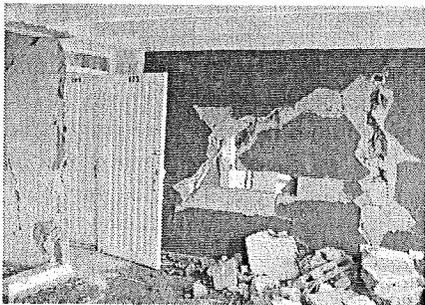


(c)

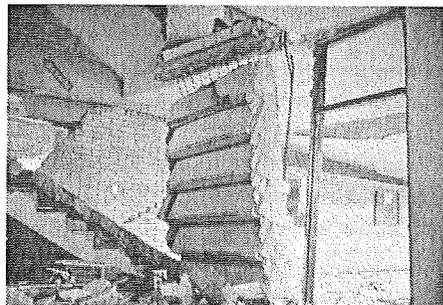


(d)

Figure 11. Damage in nonstructural elements: (a) Severe damage in masonry partitions, (b) heavy damage in stairs



(a)

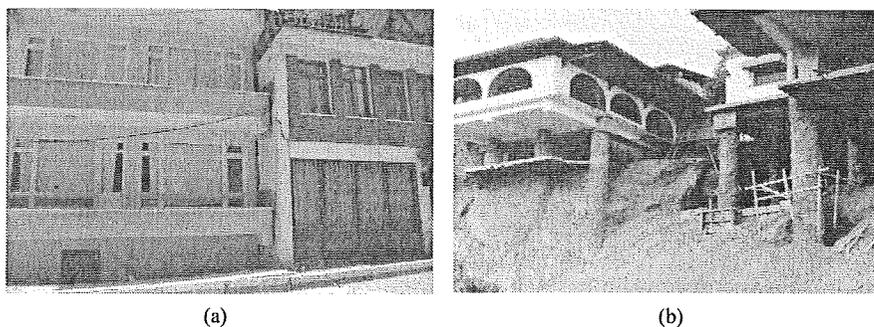


(b)

Table 2. Nonstructural elements

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

Figure 12. Ground conditions: (a) Soil settlement and liquefaction, (b) landslides and ground failure



kowska). The fuzzy rule base is the knowledge base which consists of a collection of fuzzy if-then rules.

Consequently, following the proposed fuzzy rules, the building habitability is obtained by means of structural and nonstructural evaluations but also assessing the ground conditions. Finally, using the preexistent 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 obtained from this expert system. Figure 14 shows the structure of the neural network used in the proposed model.

Figure 13. Preexistent conditions: (a) Bad construction quality, (b) vertical shape irregularities, soft floor, (c) plane shape irregularities, (d) bad structural configuration: some elements are out of the main frames

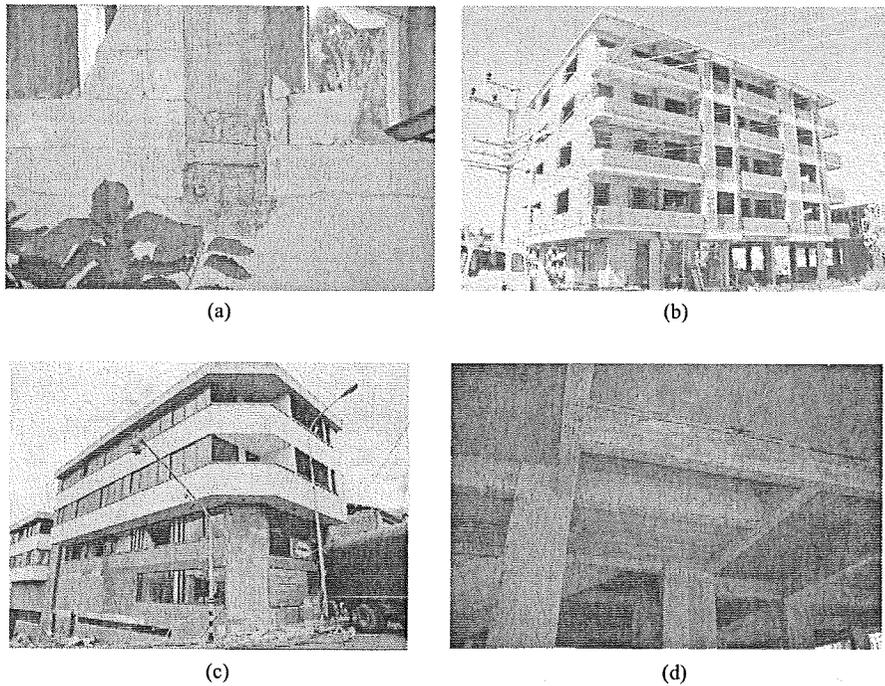
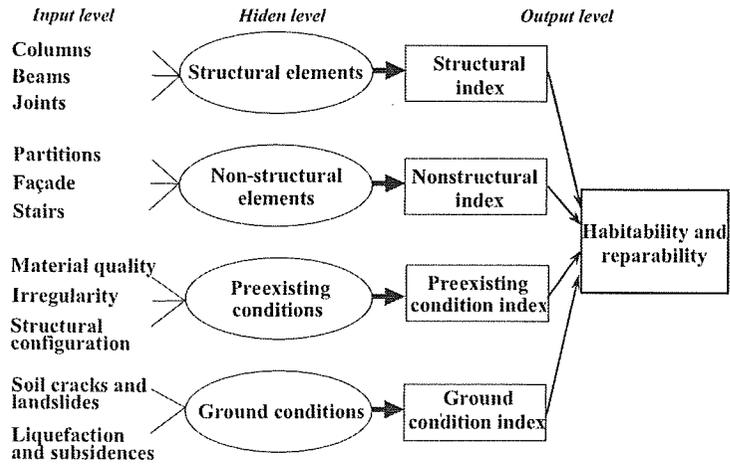


Figure 14. Structure of the neural network



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) of the input layer are obtained from the linguistic qualifications made by the inspectors after a visual inspection of the building, which provide the damage D_j at each level j and its extension or weight w_j . The damage extension, or percentage of each damage level in each element, varies from 0 to 100 and it is normalised:

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

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 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

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

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.

Intermediate or Hidden Layer of the ANN

This layer has four neurons corresponding to each group of variables: structural elements, nonstructural elements, ground conditions and preexistent conditions. Figure 15 shows a more detailed 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 from each group of neurons and its weight W_i or degree of importance on the corresponding intermediate neuron. These weights have to be defined with the participation of experts in earthquake damage evaluation. The weights considered for some structural systems are shown in Table 3, while tables 4, 5, and 6 show the weights for the nonstructural elements, ground conditions and

Table 3. Weights for structural elements according to the building type

Structural system	Beams	Columns	Joints or connections	Walls	Bearing walls	Floors
Reinforced concrete frame	19	46	25	-	-	10
Reinforced concrete structural wall	15	-	20	57	-	8
Confined masonry	-	-	-	-	73	27
Reinforced masonry					73	27
Unreinforced masonry	-	-	-	-	70	30
Bahareque walls	-	-	-	-	77	23
Steel frame	18	39	35	-	-	8
Wood frames	23	45	21	-	-	11

preexisting conditions. Using these qualifications and weights for each variable i , a global index is obtained, for each group k , from the defuzzification of the union or maximum membership of the scaled fuzzy sets:

$$I_{SE} = [\max (W_{SEi} \times \mu_{C_{SEi}} (C_{SEi}), \dots, W_{SEi} \times \mu_{C_{SEi}} (C_{SEi}))]_{centroid} \quad (5)$$

$$\mu_{CSE}(C) = \max (W_{SEi} \times \mu_{C_{SEi}} (C_{SEi}), \dots, W_{SEi} \times \mu_{C_{SEi}} (C_{SEi})) \quad (6)$$

Table 4. Weights for nonstructural elements

Element	Weight
Partitions	35
Façade	35
Stairs	30

Table 5. Weights for ground conditions variables

Element	Weight
Soil cracks and land slides	50
Liquefaction and subsidences	50

Table 6. Weights for preexisting conditions variables

Element	Weight
Materials quality	25
Plane shape irregularities	25
Vertical shape irregularities	25
Structural configuration	25

The membership functions $\mu_{C_{ki}}(C_{ki})$ and their weights W_{ki} show the notation for the group of structural elements. The groups of variables related to ground and preexisting conditions are optional; thus they can be or can be not considered within the evaluation. In this last case the habitability and reparability of the buildings is assessed only with the structural and nonstructural information.

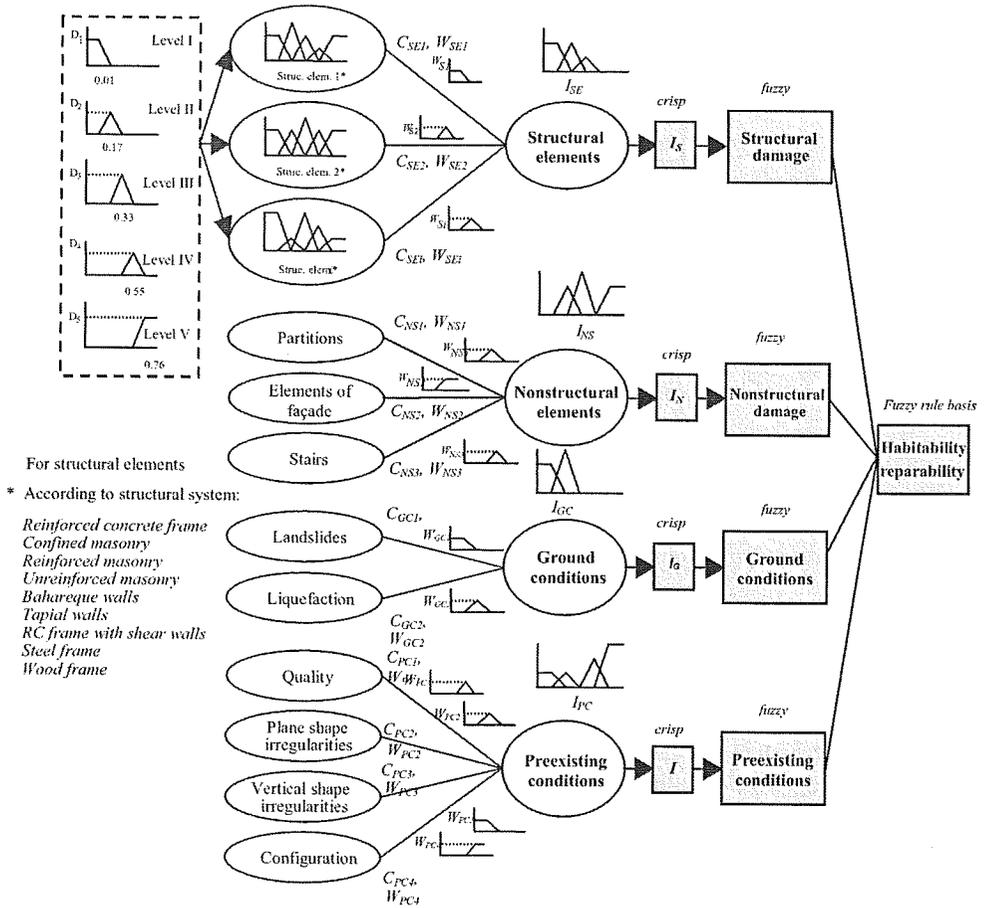
Output Layer of the ANN

In this layer, the global indices obtained for structural elements, nonstructural elements, ground and preexistent 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 (centre 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 rule bases.

Training Process of the ANN

The neural network is calibrated in the output layer where the damage functions are defined in relation to the damage matrix indices. In order to start the calibration, a starting point is defined, that corresponds to the initial indices of each level of damage. The indices proposed by the ATC-13 (ATC, 1985), Park, Ang, and Wen (1984), the fragility curves used by HAZUS-99 promoted by the Federal Emergency Management Agency (1999) and the indices used by Sanchez-Silva and García (2001) have been considered. The values of these indices correspond to the centre of area for every membership function related to each damage level. Table 7 shows the indices proposed in this work together with the indices proposed by Park et al. (1984) and Sanchez-Silva and Garcia (2001), which have been included with

Figure 15. Structure of the proposed artificial neural network



the aim of comparison. The selection of the initial indices is based on the indices of Park; this choice is justified on the basis that they have been calibrated with information of several experimental and numerical studies. Some authors consider that collapse occurs for a value equal to 0.8, although Stone and Taylor (1993) proposed a collapse threshold of 0.77. According to this opinion, a value of 0.76 has been selected to describe the collapse level index. The authors decided to be conservative when selecting the damage index, 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 case are calibrated. The network learning is made using a Kohonen network:

Table 7. Comparative table for damage indices

Damage Level	Park, Ang, and Wen	Sanchez-Silva and García	Proposed
Very light	< 0.10 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

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

where I_{kj} is the value of the index of the variables group k recalculated considering a learning rate α , 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:

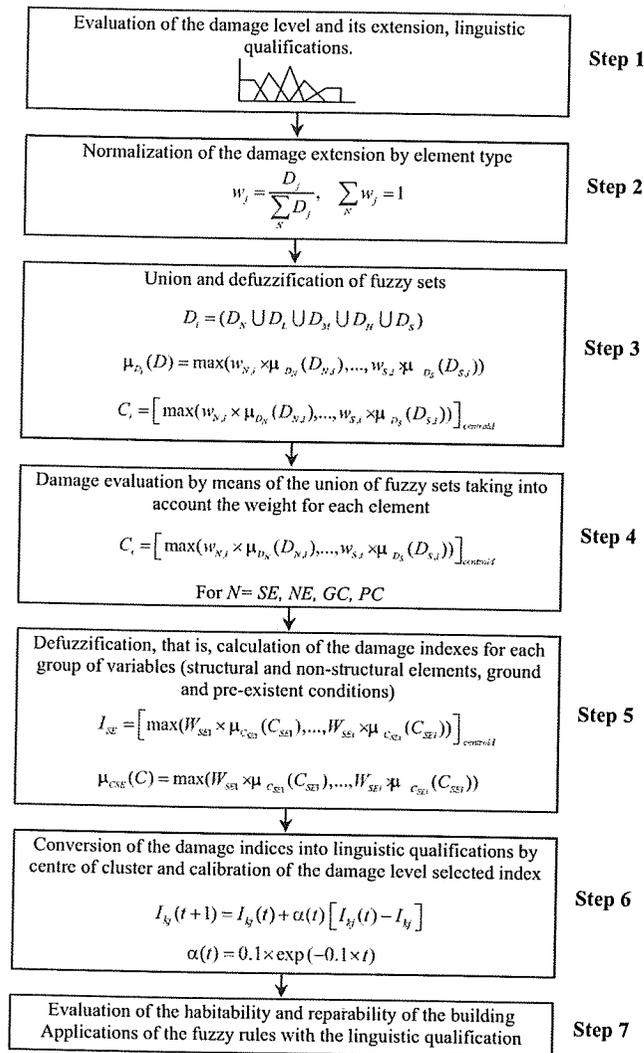
$$\alpha(t) = 0.1 \times \exp(-0.1 \times t) \quad (8)$$

where t is the number of times that has been used the index which is calibrated. For training, the damage evaluations made after the Quindío earthquake in Colombia in 1999 were used. However, more information is necessary to complete the network training for all structural classes, especially for wood and steel framed structures, because these building classes are not common in that area. Reinforced concrete frames with shear walls are also only a few and, therefore, the number of building evaluations to calibrate this structural system were insufficient. The Figure 16 shows a summary of the computational process performed by the proposed model.

Fuzzy Rule Bases For Decision Making

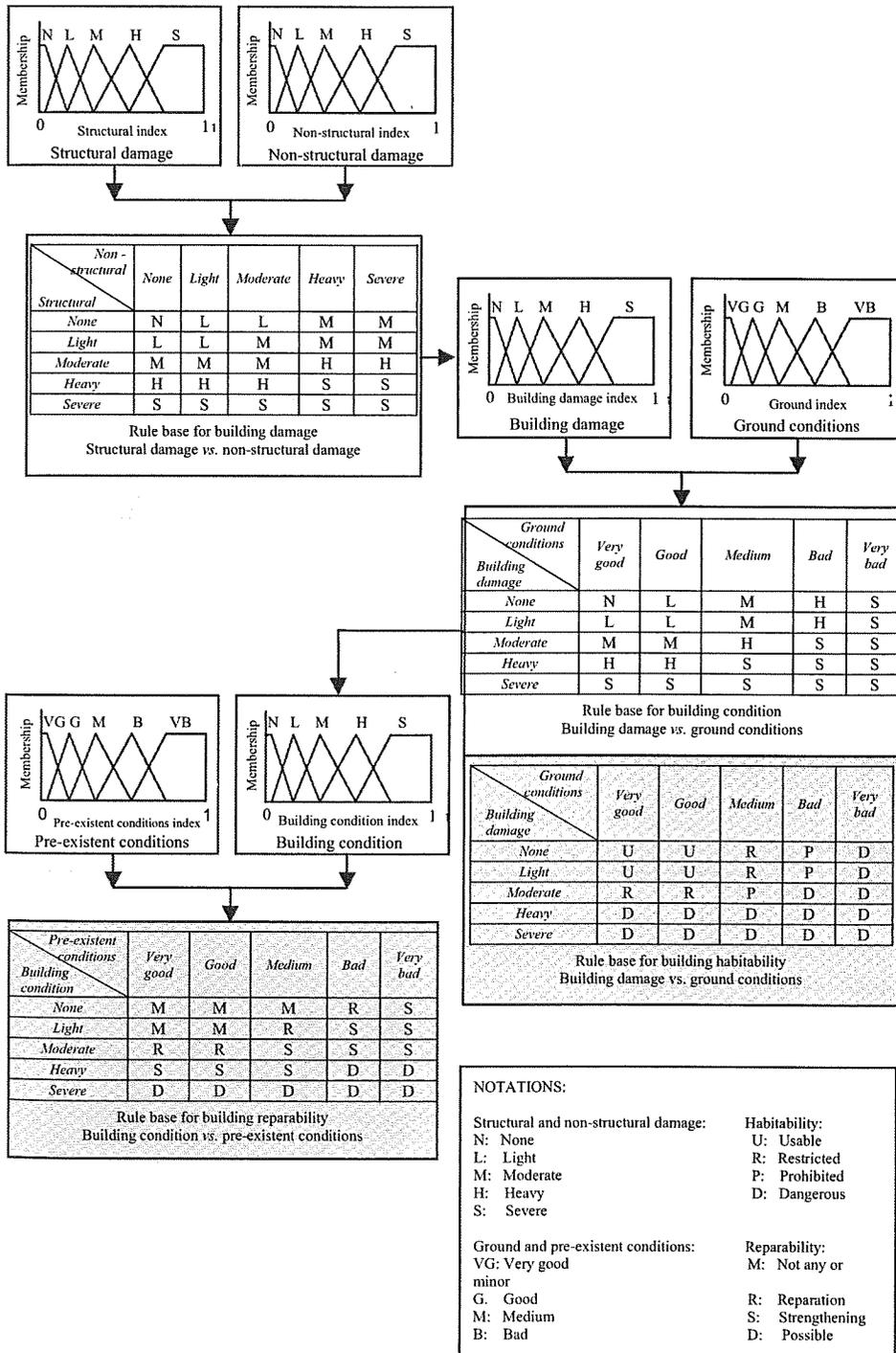
The building habitability and reparability are assessed based on previous results of the damage level of the structural and nonstructural elements, the state of the ground and of the preexistent conditions. Figure 17 displays the used fuzzy rule bases. The global level of the building damage is estimated starting from the structural and nonstructural damage results. The global

Figure 16. Flow chart for the evaluation process



building state is determined taking into account the rule bases of the ground conditions and, by this way, the habitability of the building is obtained. 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. Besides, the building reparability depends on other fuzzy rule bases: the preexistent conditions. The building reparability has four possibilities: not any or minor treatment, reparation, reinforcement, and possible demolition.

Figure 17. Method for building habitability and reparability



Examples of Evaluation Using the Proposed Computational Model

In this section are given three examples which illustrate the application of the proposed model to the evaluation of the seismic damage and safety of three buildings having different typologies: reinforced concrete, unreinforced masonry and confined masonry. These buildings have been damaged by the January 1999 earthquake occurred in the coffee-growing-area of Colombia. The most important characteristics of each building are given, together with the damage level and extension corresponding to each type of structural and nonstructural element. Photos of the most characteristic damage observed after the earthquake are shown. The results obtained for each example correspond to four aspects of the problem: damage, risk, habitability and reparability, and are given in four sections of a table. The section of damage provides as results numerical and linguistic qualifications for each group of elements. The section of risk gives a qualification of the risk level corresponding to the structure, the nonstructural elements and to the ground and also evaluates the overall state of the building. The habitability section provides a decision about the building habitability and suggests security measures to be undertaken urgently. The reparability section suggests certain measures which have to be applied, but without a detailed description. Obviously, the detailed repair measures require the intervention of a structural engineer. All the numerical and linguistic results, comments and descriptions are given by a computer program in which the proposed model has been implemented. At present, this program, Earthquake Damage Evaluation of Buildings (EDE), is used as an official tool by the disaster risk management offices of the cities of Bogotá and Manizales, in Colombia. At the end of the table which describes the result for each example, a flow chart is included, which describes the application of the fuzzy rule basis in order to obtain the qualification of the building damage state, habitability and reparability.

Example 1.

General information	
<i>Building inspection:</i>	Outside and inside
<i>Construction year:</i>	1950 to 1984
<i>Number of stories above ground:</i>	5
<i>Bellow ground:</i>	0
<i>Structural system:</i>	Reinforced concrete frame
<i>Kind of diaphragms</i>	Solid slabs
<i>Localization in block:</i>	Corner

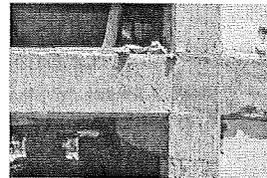


General conditions of the building	
<i>Collapse:</i>	Not
<i>Building or any story tilting:</i>	Not
<i>Failure or settlement in the foundation:</i>	Not
<i>Story with the most damage:</i>	3

Damage in structural elements					
<i>Beams:</i>	None: 70	Light: 30	Moderate: 0	Heavy: 0	Severe: 0
<i>Columns:</i>	None: 45	Light: 50	Moderate: 5	Heavy: 0	Severe: 0
<i>Joints:</i>	None: 80	Light: 20	Moderate: 0	Heavy: 0	Severe: 0
<i>Floors (slabs):</i>	None: 40	Light: 60	Moderate: 0	Heavy: 0	Severe: 0



Column with moderate damage



Beam and slab with light damage

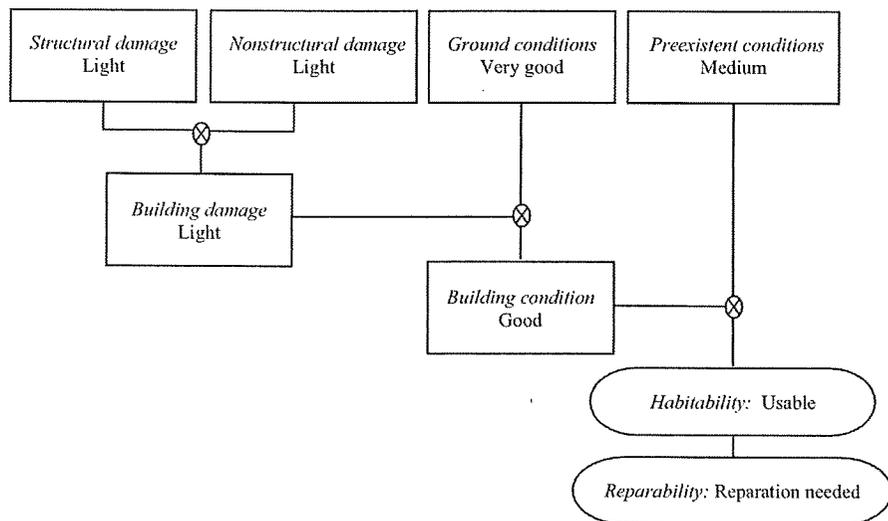
Damage in non structural elements			
<i>Partitions:</i>	Moderate	<i>Façade:</i>	Light
		<i>Stairs:</i>	None
		Partitions with moderate damage	

Ground conditions	
<i>Crack, slope instability and landslide:</i>	None (very good)
<i>Ground settlement and liquefaction:</i>	None (very good)

Preexistent conditions	
<i>Material and construction quality:</i>	Good
<i>Irregular configuration in plan:</i>	Medium
<i>Vertical irregularities or discontinuities:</i>	Medium
<i>Structural configuration:</i>	Poor (bad)

Results Example 1:

Damage	<p><i>Structural damage:</i> Light 0.1519</p> <p><i>Non structural damage:</i> Light 0.2395</p> <p><i>Ground conditions:</i> Very good 0.0541</p> <p><i>Preexistent conditions:</i> Medium 0.33</p>
Risk	<p><i>Structural risk:</i> Low</p> <p><i>Non structural risk:</i> Low</p> <p><i>Ground risk:</i> Low</p> <p><i>Building damage:</i> Light</p> <p>The building has structural and nonstructural slight damage. The earthquake resistance has been not reduced</p> <p><i>Building condition:</i> Good</p> <p>The state of the building and the ground conditions are good</p>
Habitability	<p>Usable</p> <p>The building can be normally inhabited</p> <p><i>Security measures:</i> It is not necessary to take security measures in particular</p>
Reparability	<p>Reparation needed</p> <p>The building needs some reparation possibly due to minor damages and preexistent conditions. Since the building was constructed between 1950 and 1984, it may need a structural reinforcement to be adapted to the current regulations for the earthquake resistant construction. It is recommended to undertake a study of seismic vulnerability</p>



Example 2.

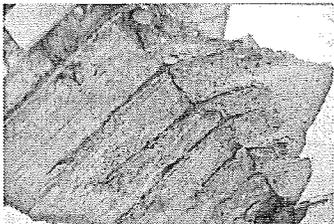
General information		
<i>Building inspection:</i>	Outside and inside	
<i>Construction year:</i>	1950 to 1984	
<i>Number of stories above ground:</i>	.3	
<i>Bellow ground:</i>	0	
<i>Structural system:</i>	Unreinforced masonry	
<i>Type of diaphragms</i>	Solid slabs	
<i>Localization in block:</i>	Intermediate	

General conditions of the building	
<i>Collapse:</i>	Partial
<i>Building or any story tilting</i>	Not
<i>Failure or settlement in the foundation:</i>	Not
<i>Story with the most damage:</i>	1

Damage in structural elements					
<i>Bearing walls:</i>	None: 0	Light: 0	Moderate: 30	Heavy: 20	Severe: 50
<i>Floors (slabs):</i>	None: 0	Light: 0	Moderate: 30	Heavy: 60	Severe: 10



Severe damage in bearing walls of unreinforced masonry (partial collapse)

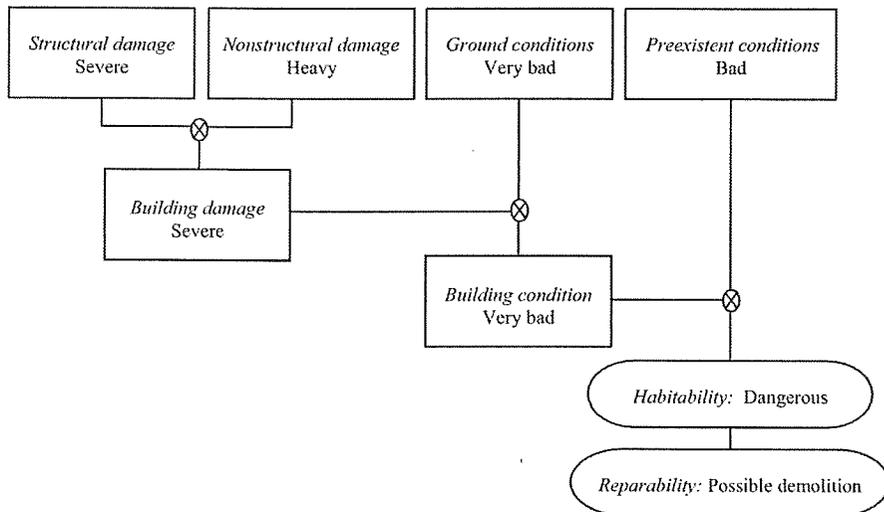
Damage in non structural elements		
<i>Partitions:</i>	Heavy	<i>Façade:</i> Heavy <i>Stairs:</i> Heavy
	Stairs with heavy damage (below)	

Ground conditions	
<i>Crack, slope instability and landslide:</i>	Widespread (very bad)
<i>Ground settlement and liquefaction:</i>	Widespread (very bad)

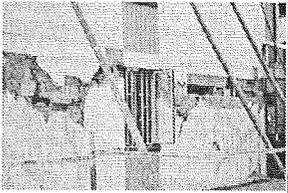
Preexistent conditions	
<i>Material and construction quality:</i>	Poor (very bad)
<i>Irregular configuration in plan:</i>	Very bad
<i>Vertical irregularities or discontinuities:</i>	Very bad
<i>Structural configuration:</i>	Very bad

Results Example 2:

Damage	<p><i>Structural damage:</i> Severe 0.76</p> <p><i>Non structural damage:</i> Heavy 0.5533</p> <p><i>Ground conditions:</i> Very bad 0.76</p> <p><i>Preexistent conditions:</i> Bad 0.6537</p>
Risk	<p><i>Structural risk:</i> Very high</p> <p><i>Non structural risk:</i> High</p> <p><i>Ground risk:</i> Very high</p> <p><i>Building damage:</i> Severe</p> <p>The building suffered severe structural damage and strong nonstructural damage. The building partially collapsed or suffered damage that puts the building in danger of collapse.</p> <p><i>Building condition:</i> Very bad</p> <p>Severe damage of the building and the very bad ground conditions; due to this situation the building condition is very bad.</p>
Habitability	<p>Dangerous</p> <p>The building habitability should be prohibited due to the danger of collapse by very bad building and ground conditions.</p> <p><i>Security measures:</i> Exterior barriers should be installed for preventing the traffic of cars and pedestrians close to the building.</p>
Reparability	<p>Possible demolition</p> <p>The building possibly needs to be demolished due to the very bad conditions of the building and the ground.</p>

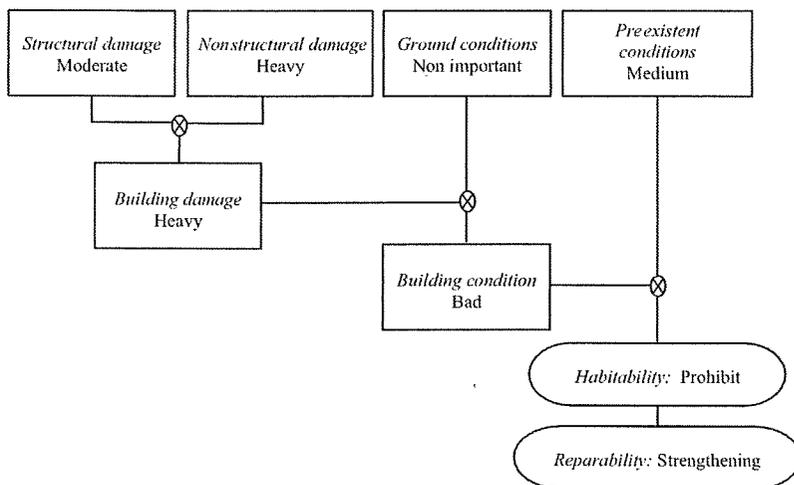


Example 3.

General information <i>Building inspection:</i> Outside and inside <i>Construction year:</i> 1985 to 1997 <i>Number of stories above ground:</i> 3 <i>Bellow ground:</i> 0 <i>Structural system:</i> Confined masonry <i>Type of diaphragms:</i> Solid slabs <i>Localization in block:</i> Free by all sides					
General conditions of the building <i>Collapse:</i> Not <i>Building or any story tilting:</i> Not <i>Failure or settlement in the foundation:</i> Not <i>Story with the most damage:</i> 1					
Damage in structural elements					
<i>Bearing walls:</i>	None: 20	Light: 30	Moderate: 50	Heavy: 0	Severe: 0
<i>Floors (slabs):</i>	None: 10	Light: 40	Moderate: 50	Heavy: 0	Severe: 0
					
Moderate damage in confined masonry bearing walls					
Damage in non structural elements <i>Partitions:</i> Heavy <i>Façade:</i> Heavy Ground conditions <i>Crack, slope instability and landslide:</i> Not important (very good) <i>Ground settlement and liquefaction:</i> Not important (very good)		<i>Stairs:</i> Heavy			
Preexistent conditions <i>Material and construction quality:</i> Poor (very bad) <i>Irregular configuration in plan:</i> Significant (Medium) <i>Vertical irregularities or discontinuities:</i> Significant (Medium) <i>Structural configuration:</i> Poor (very bad)					

Results example 3

Damage	
<i>Structural damage:</i>	Moderate 0.35
<i>Non structural damage:</i>	Heavy 0.5533
<i>Ground conditions:</i>	Not important information
<i>Preexistent conditions:</i>	Medium 0.35
Risk	
<i>Structural risk:</i>	Low, after some measures
<i>Non structural risk:</i>	High
<i>Ground risk:</i>	Low
<i>Building damage:</i>	Heavy
	The building suffered moderate structural damage and heavy nonstructural damage that can affect the structural stability in case of an aftershock. The earthquake resistance has been reduced.
<i>Building condition:</i>	Bad
	The building was seriously damaged although the ground conditions are good.
Habitability	
	Prohibited
	The building occupancy is dangerous due to the bad conditions of the building
<i>Security measures:</i>	It is necessary to remove and to anchor the elements that can collapse, to demolish some nonstructural elements and to install internal barriers to mark the high risk zones.
Reparability	
	Strengthening
	The building needs reinforcing due to its general bad conditions and the medium preexistent conditions. In this case, an expert structural engineer must be consulted to make a decision.



Conclusion and Future Trends

As a support to the complex task of building damage evaluation after an earthquake, an innovative expert system has been proposed, based on computational intelligence techniques such as artificial neural networks and fuzzy logic approach. This computational model improves the existing conventional existing methodologies, making possible a more accurate seismic building damage evaluation by nonexpert professionals. This type of tool is suitable in the practice because building damage evaluation deals with subjective and incomplete information which requires the use of linguistic qualifications that are appropriately handled by fuzzy sets. In addition, an artificial neural network has been used to calibrate the system using the judgment of specialists. The training of the neural network was performed by using a database of real evaluations made by expert engineers.

The proposed neuro-fuzzy expert system enabled the development of a user-friendly computer program called *Earthquake Damage Evaluation of Buildings, EDE*. At present, this program is used as an official tool by the disaster risk management offices of the cities of Bogotá and Manizales, in Colombia, and it is a component of a "National Program on Building Evaluations," in which new inspection guidelines and forms have been also developed.

The possibility of calibrating the expert system to be used directly in different seismic areas depends on the use of accurate and reliable databases of building damage obtained by means of inspections and qualifications made by experts. These databases are essential because it is necessary to have available detailed and relevant damage information for the learning process of the artificial neural network. Unfortunately, these databases are not available at present in the desired amount. Therefore, in order to refine the quality of the proposed expert system, it is necessary, throughout the coordination of professional associations of earthquake engineering and universities, to develop appropriate databases of evaluations after future earthquakes, taking into account all the building types existing in the seismic areas, to complete the learning process for these constructions. Any way, more information on the structural types for which evaluation databases are already available is also desirable in order to improve the knowledge on the seismic behaviour of buildings having the same type but which are located in different areas and, therefore, have different details.

Although it would be also possible to perform future developments in the field of damage evaluation algorithms, first of all it is necessary to improve the data collection of building damages and the organization of procedures and of the coordination of the emergency response after earthquakes. The current conventional methodologies are well designed but their implementation is still not adequate. The possibility of avoiding mistakes made by nonexperts is far to be assured if a tool, like the expert system here described, is not available in the time of a strong earthquake.

Lastly, the use of soft computing is relevant in many activities of civil engineering, in which computational intelligence tools can be successfully applied; however, they had not an appropriate diffusion until present. Therefore, it is recommended to promote their use to provide suitable and versatile solutions to several problems in this field of knowledge.

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