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Post-earthquake assessment of buildings damage using fuzzy logic

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ABSTRACT

The present paper develops a methodology based on fuzzy logic for post-earthquake assessment of buildings damage. It derives the global building damage level from that reported information by trained technical staff, after in-situ visual inspection of the main parameters, i.e., the "Structural components" and the "Non-structural components". For illustration purposes, thousands of evaluation forms from post-earthquake survey following the 2003 Boumerdes, Algeria, earthquake (Mw = 6.8) have been collected. According to the standard evaluation form, each component's damage is ranked from D_1 (No damage) up to D_5 (Collapse). The aim is then to derive the global damage level of buildings which should also rank from D_1 to D_5. The paper investigates the effect of the number and weights of fuzzy rules to relate each components' damage level to the global damage level using a single-antecedent weighted fuzzy rule. It investigates also the effect of membership functions values so that it is possible to consider one damage level as the most dominant with highest membership value whereas the rest damage levels are still considered although with lower influence. A genetic algorithm is adopted to optimize the rule weights associated to the components' damage levels. The collected database which covers more than 27,000 buildings is used to train and validate the procedure. The theoretical prediction, obtained by automatic processing of the evaluation form for each building, is compared to the global damage (observed damage) identified by inspectors. Results show that the theoretically-based evaluation is in accordance with the observed values for 90% of the investigated buildings.

1. Introduction

Earthquakes are one of the most natural destructive phenomena. They have repeatedly caused considerable losses and casualties in many parts around the world [1]. The frequent occurrence of earthquakes and their consequences in terms of losses got the attention of public authorities of many countries, leading to the development and regularly update their seismic design code to better enhance the performance of buildings during earthquakes. However, numerous buildings have been built with obsolete seismic codes or even without applying any seismic codes and these buildings are mostly more vulnerable to earthquakes and experience more damage.

After an earthquake, experts are deployed for post-earthquake damage survey to assess the incurred damage. One of the main objectives of the assessment tasks is the evaluation and the classification of buildings into different categories with respect to their damage levels. Many damaged buildings are sensitive and hazardous, especially when an aftershock ground shaking occurs. The unsafe buildings must be marked to be evacuated and restricted from occupancy. This classification helps to decide which buildings are safe to occupy, which need more detailed evaluations for reparation and retrofitting purposes, and which are condemned to demolition.

Affected and potentially damaged buildings are usually classified using global damage levels. Global levels are determined according to the observed damage on each of the buildings' components. These components are generally divided into two main categories, i.e. "Structural components" *(columns, beams, walls, slabs, etc.)* and "Non-structural components" *(staircases, separation walls, facade, balconies, etc.)*. The structural components are the most important part, from the mechanical point of view, as they provide the bearing capacity to the horizontal and vertical loads which refer directly to the stability and the safety of the building. The lack of resistance in these components increases the potential collapse of the building.

On the other hand, non-structural components are not less important, since severe damage in these components refers sometimes to the fact that the building's seismic capacity is decreased. Furthermore, the non-structural components ensure the usability of the building and their cost represents the majority of the building's worth [2–4]. Multiple other hazards like soil condition around the building are also involved during the assessment procedures in different guidelines [2,5].

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Several post-earthquake assessments and seismic vulnerability guidelines are proposed in the literature. These guidelines vary in their level of inspection from rapid screening to detailed evaluation [6–10]. They provide evaluation forms to be filled in by inspectors during the assessment task by performing a walk-down survey in order to make their judgment, i.e. building's damage level, building's seismic vulnerability and building's usability.

However, a rigorous assessment of post-earthquake damage is a very difficult and delicate task and subject to uncertainty due to many factors. Uncertainties make the procedure more difficult and challenging. Multiple factors that cause uncertainties and doubts are a concern during assessment campaigns. Hence, some major factors are described, after massive earthquakes; the assessment tasks are conducted under emergency situations where neither the time nor the necessary equipment is adequately provided to inspectors. Under such conditions, the inspectors face major difficulties to provide reliable judgments. Again, the interpretation of damage indicators varies among the inspectors since it is based mostly on visual inspection. Guidelines which provide damage levels classification use quantitative terms to describe the intensity of damage, such as: "*No damage*", "*Slight damage*", "*Moderate damage*", "*Heavy damage*" and "*Collapse*". That is to say, multiple damage levels are proposed and a common definition of damage levels is not yet achieved. Furthermore, damage levels are often discrete categories and lack clear definitions. Thus, vague language makes the boundaries between damage levels blurry. The interpretation of damage levels definitions varies between inspectors. That is to say, it is hard to tell when a damage in a building's component has reached or exceeded a particular damage level only by visual inspection. Each component has its specification and its relative importance according to its functionality, its position, and its behavior during earthquakes. For example, lower stories with their components have more relative importance than upper stories. However, the level of understanding of these features affects the reasoning of inspectors during the assessment tasks.

Huge and complex buildings are always difficult to be assessed. For this, the structural system of the building must be identified first. Components of different structural systems behave differently during earthquakes. The global damage level is related to local components' damage levels. It is always challenging to determine the influence of each component on the global response of the structure and a high number of components makes the derivation of a global damage level more difficult to inspectors. Thus, such scenarios contain large degrees of uncertainty for inspectors and accurate evaluations are always critical.

Many buildings are built with poor quality control. Despite the fact that the buildings might or might not be built according to a modern seismic code, such buildings cannot ensure enough seismic performance. Such information (the applied seismic code) can sometimes mislead the inspectors. Therefore, the inspector must rely more on his engineering judgment. Another factor is raised when the building has suffered damage to their facades, cladding and architectural parts, whereas the structural system remains intact or suffer minor damage. Such building can mislead the inspectors and may be classified as unsafe while they can be occupied. On the other hand, other buildings can lack of visible evidence of heavy structural damage and this damage is covered by the building's cladding or architectural parts. Such buildings represent a real threat to occupants and require special attention from the inspectors.

Expert systems became a vital tool nowadays. They are used to solve complex problems and to help experts during their decision-making processes. The applications of expert system extend and reach almost all engineering fields. Moreover, expert systems use artificial intelligent theories (e.g., *Neural Network, Fuzzy Logic, Genetic Algorithms, Rule-Based Systems, Knowledge-Based Systems*) and stored human knowledge to simulate the judgment and behavior of experts to conduct expertise and propose conclusions [11,12].

A support decision tool can provide a great help and assistance to inspectors and minimize the range of error during the assessment of the seismic risk. Hence, several researches are conducted to apply artificial intelligent theories to build expert systems for pre- and post-earthquake assessment models. Many methodologies have been developed worldwide to assist the inspectors during their assessment procedures: Sanchez-Silva and Garcia [13], Demartinos and Dritsos [14], Sextos et al. [15], Carreño et al. [16], Tesfamariam and Saatcioglu [17], Şen [18], Mebarki et al. [19]. However, the development of expert systems is a difficult task by itself. Highly performed systems require sound experts' knowledge and clear development methodologies in which simple ones are always suitable to develop such systems.

In this paper, an automatic processing methodology is described to build fuzzy systems with an application to post-earthquake damage assessment procedure based on the theory of fuzzy logic, approximate reasoning, weighted fuzzy rules and fuzzy inference methods. It investigates the effect of the number and weights of fuzzy rules where each component's damage level is related to the global damage level by a single-antecedent weighted fuzzy rule. The proposed methodology aims to process relevantly the damage of the building's components in order to derive rigorously the global damage level of the whole building.

2. Post-earthquake damage assessment: General aspects

The purpose of the present study is to develop a general automatic processing methodology with an application to post-earthquake damage evaluation surveys and their evaluation forms. These forms are filled out after visual inspections of buildings in the aftermath of an earthquake. For illustrative purposes, the standard evaluation form used in Algeria [20] is considered in order to present the proposed methodology, see Appendix A.

The evaluation form contains sections to systemize the evaluation procedure. Each section contains selected sub-components to be assessed jointly. Besides, each sub-component should be represented by the maximum observed damage in that category, (e.g., if various damage levels are observed on concrete columns, only the maximum damage level should be assigned). The inspector is expected to inspect visually the building's components and fill out the evaluation form on a scale from D_1 (No damage) up to D_5 (Collapse). Finally, the inspectors assign the global damage level also on a scale from D_1 up to D_5 by analyzing the assigned damage levels in the form's sections. The building's safety and usability are determined accordingly using appropriate tag colors, i.e.: *Green* for safe, *Orange* for unsafe and *Red* for dangerous, see Table 3.

Previous studies based on probabilistic approach and on Artificial Neural Network concept, in which the standard evaluation form used in Algeria was discussed, have shown that global damage level depends mostly on the observed damage on each of the governing parameters, i.e. "Structural or Primary" components and "Non-structural or Secondary" components [19,21], see Tables 1 and 2. The global damage level of any inspected building can then be written under a general form as a function of components' damage levels:

$$D_G = D_G(d_1,\ldots,d_k,\ldots,d_{N_c}) \tag{1}$$

$$N_c = N_S + N_{nS} \tag{2}$$

where: D_G = global damage level; d_k = damage level of the k-*th* component with $k = 1,\ldots,N_c$; N_c = total number of components considered as governing parameters, i.e. "Structural" components *(columns, beams, walls, slabs, etc)* which number is N_S and "Non-structural or Secondary" components *(staircases, separation walls, facade, balconies, etc)* which number is N_{nS}. These damage levels (D_G and d_k) range within the interval [1. .5], see Table 3.

$$D_G \in \{D_1,D_2,D_3,D_4,D_5\},\ d_k \in \{d_1,d_2,d_3,d_4,d_5\} \tag{3}$$

Table 1
Structural components [19,21], see Appendix A.

Sub-structural components	Vertical load carrying components	Lateral load resisting components	Flat roofs and floors	Sloped roofs
- Continuous concrete walls - Concrete columns with infill	- Masonry walls - Concrete walls - Concrete columns - Steel columns - Wood columns - Others	- Masonry walls - Concrete walls - Reinforced concrete frames - Steel frames - Cross-braced frames - Others	- Reinforced concrete - Steel joists - Wooden joists	- Steel truss - Wood truss - Tile roof - Asbestos cement sheet roof - Corrugated metal roof

Table 2
Non-structural components [19,21], see Appendix A.

Staircases	Interior components	Exterior wall panels	Exterior components
- Concrete - Metal - Wood	- Ceilings - Partitions - Glass	- Masonry - Precast concrete - Corrugated metal - Others	- Balconies - Railings - Overhangs - Parapets – cornices - Chimneys - Others

3. Fuzzy logic approach: Theoretical aspects

3.1. Theoretical framework

The Mamdani-type fuzzy system is adopted [22] in the present theoretical framework with an application of the standard evaluation form used in Algeria which leads to the development of the proposed fuzzy logic model (see Fig. 1). The model derives the global damage level D_G^* of the building from the observed damage on the components, e.g., the "Structural" and the "Non-structural" components according to previous studies [19,21]. It derives also intermediate outputs which are the structural damage level D_S^* and the non-structural damage level D_{nS}^*.

Thus, by following Eq. (1), the global damage can be defined as a function of the considered governing parameters:

$$D_G = D_G(\mathbb{1}_k.\ d_k),\ k = 1,\dots,N_c \tag{4}$$

With:

$$\mathbb{1}_k = \begin{cases} 1: & if\ the\ k\text{-}th\ component\ is\ a\ governing\ parameter \\ 0 & otherwise \end{cases} \tag{5}$$

3.2. Fuzzy parameters development

The proposed fuzzy logic theoretical framework can be described by the following steps:

- Selection of sub-fuzzy systems *(Groups)* which are supposed to influence the global damage level: they usually represent the evaluation form's sections. Thus, the selection of the *Groups* follows parameters of the assessment methodology in question, for instance, the Algerian post-earthquake damage assessment methodology: three *Groups* are considered in this study, see Fig. 1:
  - ***Group 1:*** "*Structural damage level:* D_S^*" involves 5 components named as "*Structural components*", i.e.: Sub-structural components SC, vertical load carrying components VC, lateral load resisting components LC, flat roofs & floors FR and Sloped roofs SR, see Table 1.
  - ***Group 2***: "*Non-structural damage level:* D_{nS}^*" involves 4 components named as "*Non-structural components*", i.e.: Staircases ST, interior components IC, exterior wall panels EW and exterior components EC, see Table 2.
  - ***Group 1–2***: "*Global damage level:* D_G^*" involves the obtained results from the previous *Groups*, i.e. *Structural* and *Non-structural damage levels*.
- Definition of fuzzy logic parameters: these parameters describe the relationship between the components' damage and the global damage level of the building. For this purpose, it is required that fuzzy sets and their membership functions should be adequately identified:
  - ***Fuzzy sets:*** For each component, each damage level in Eq. (3) is represented by a fuzzy set A_k with its membership function $\mu(d_k)$, that is, fuzzy sets are always defined as a pair, see Eqs. (6) and (7). Although various membership functions forms could be adopted, the most frequently used triangular membership functions are adopted in the present study [22], see Fig. 2:

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

$$\mu(d_k) \in [0,1] \tag{7}$$

The Eq. (7) values (membership values) are assigned by the fuzzy system during the assessment tasks according to the inspector's inputs. It is a fact that sometimes inspectors hesitate, one damage level is too low and the next damage level is too high to classify the observed damage, instead of being forced to choose one damage level, fuzzy logic allows inspectors to classify the observed damage within the

Table 3
Description of damage levels [19,21], see Appendix A.

Damage level	Tag color	Damage Intensity	Description	*Decision*
D_1, d_1	Light Green	No damage (D_1)	No damage.	*No evacuation needed.*
D_2, d_2	Dark Green	Slight damage (D_2)	Isolated non-structural damage, cracks in the interior walls or ceilings, damage in water lines, …	*No evacuation needed but need to slight repair*
D_3, d_3	Light Orange	Moderate damage (D_3)	Significant non-structural damage and slight structural damage.	*Evacuate until repair and strengthening*
D_4, d_4	Dark Orange	Severe damage (D_4)	Heavy non-structural damage and important structural damage.	*Evacuate until repair and strengthening*
D_5, d_5	Red	Collapse (D_5)	Collapsed buildings or condemned to demolition.	*Evacuate and demolish*

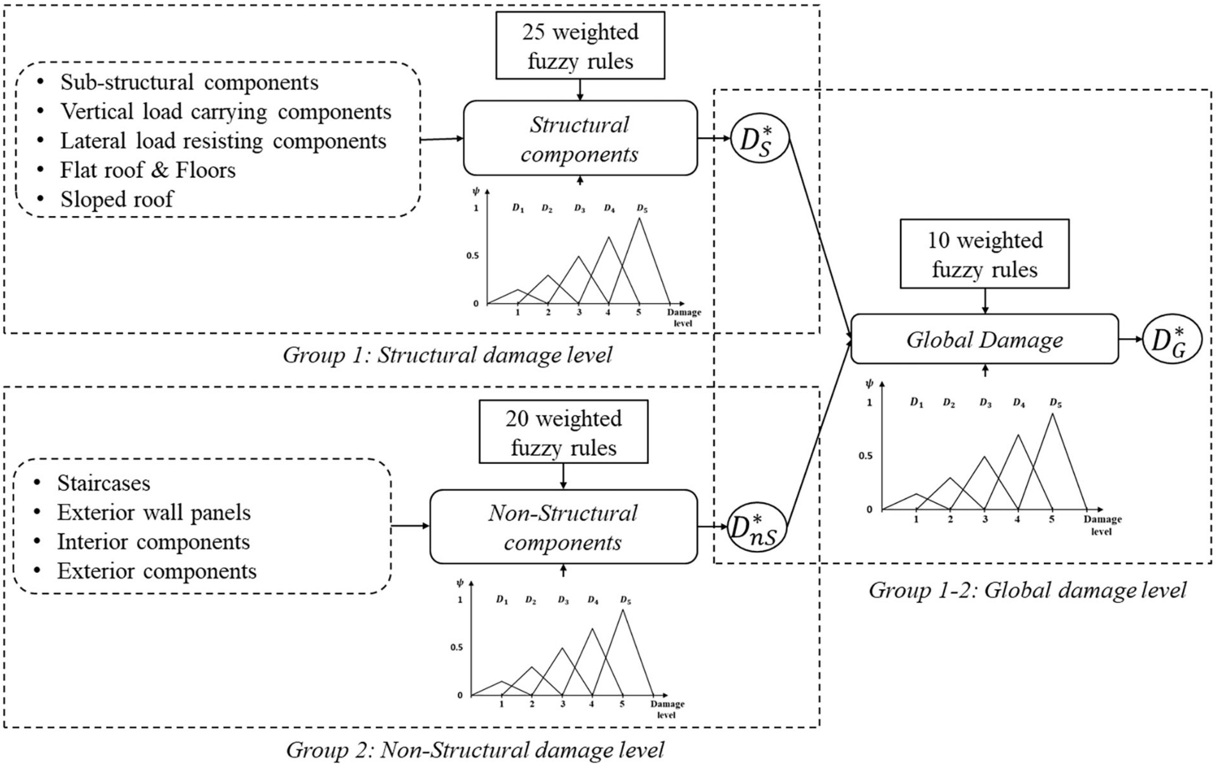

Fig. 1. The proposed fuzzy logic approach flowchart.

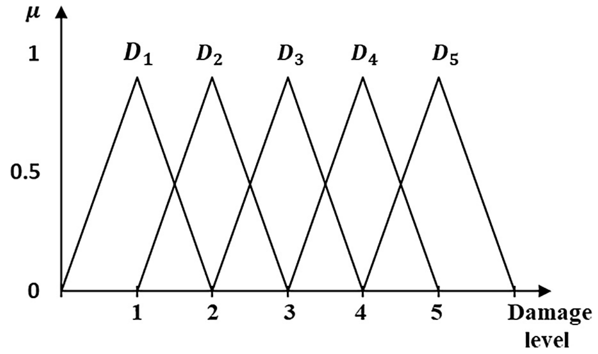

Fig. 2. Representation of damage levels using triangular membership functions.

overlapped limits of damage levels (see Fig. 2), the engaged damage levels d_k contribute in the defuzzification according to their $\mu(d_k)$ values [23].

- ***Fuzzy rules:*** Generating efficient fuzzy IF-THEN rules is important in fuzzy logic modeling since they affect directly the performance of the system [24], fuzzy rules required either sound human experts' knowledge or large data and computation efforts to be generated effectively [25]. In this study, a novel application of weighted fuzzy rules is proposed, weighted fuzzy rules are adopted to express weighted relationships between the components' damage d_k and the target damage level (i.e.: D_S^*, D_{nS}^*, D_G^*) as "Weighted damage levels".

For each *Group* (sub-fuzzy system), fuzzy rules are coded using single-antecedent weighted fuzzy rules [26] to express short and simple statements:

$$R_j\text{: if } d_k \text{ is } d_0 \text{ then } D^* \text{ is } D_0 \text{ with } \omega_k,\ j = 1,\ldots,N \tag{8}$$

And:

$$\omega_k \in [0,1] \tag{9}$$

where: d_0 = observed damage level for the k-*th* component during the visual inspection by the inspector. It takes one of the possible levels of damage in the adopted assessment methodology, D_0 = corresponding damage level to be assigned to the target damage level, it takes the same damage level as the observed damage d_0. See Table 3 and Eq. (3). ω_k = associated rule weight of the d_k damage level of the k-*th* component. The values of ω_k are calibrated during an optimization process. Each weighted rule can be interpreted as follows: for instance, **if** the examined component k-*th* suffers moderate damage (d_k is d_3) **then** the target damage level (i.e.: D_S^*, D_{nS}^* and D_G^*) takes the same damage level (D^* is D_3) **with** considering its corresponding weight ω_k. N = number of required rules for the k-*th* component according to the number of adopted damage levels. For this study, five damage levels from "D_1: No damage" to "D_5: Collapse" require five weighted fuzzy rules for each component.

- Definition of theoretical damage level: The target damage level could be expressed using the well-adopted *Centroid* (*Center of gravity*) defuzzification method [23] due to their properties. Defuzzification methods are usually selected depending on the characteristics of the modeled problem. Various defuzzification methods are also developed beside *Centroid* such as the *Maxima* methods (e.g., *first of maxima*, *last of maxima*, *mean of maxima*, …) [27]. However, these methods are not suitable for the present study since they produce values for which the output is maximum and that eliminates the effect of rule weights during the defuzzification. The proposed improvement consists in adopting a rigorous *Centroid* definition by including rule weights [26,28] so that the target damage level (e.g. D_G^*) becomes, see Fig. 3:

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

which contracted form becomes:

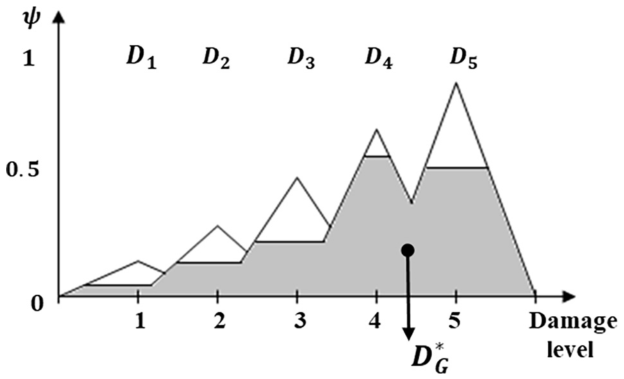

Fig. 3. Representation of the adopted centroid method using weighted damage levels.

$$D_G^* = \frac{\sum_{k=1}^{N_c} \mathbb{1}_k \cdot D_k \cdot \psi_k}{\sum_{k=1}^{N_c} \mathbb{1}_k \cdot \psi_k} \tag{11}$$

With:

$$\psi_k = \mu_k(D_k) \cdot \omega_k \tag{12}$$

- ψ_k is considered as coefficient of weighting. It calibrates the effect of the observed damage in its correspondent components on the target damage level (i.e.: D_S^*, D_{nS}^*, D_G^*). Components with high ψ_k values have higher influence on the target damage level, see Eqs. (11) and (12).

4. Fuzzy rule weights: Identification

4.1. Theoretical developments

The fuzzy rule weights need to be adequately calibrated, experts' opinions can be adopted as an approach to calibrate these weights. However, a database collected during a past earthquake is adopted in this study in order to calibrate the weights through an optimization process. The values of ω_k are the solution of the following optimization problem:

$$Minimize\ \chi^2 \tag{13}$$

With:

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

N_b = total number of buildings under evaluation; $D_G^*(i)$ = predicted global damage for any i-*th* building (see Eq. (10)); $D_G^{obs}(i)$ = its corresponding observed global damage.

The objective function to be minimized can then be expressed as:

$$\chi^2 = \frac{1}{N_b} \sum_{i=1}^{N_b} \left(\left. \frac{\sum_{k=1}^{N_c} \mathbb{1}_k \cdot \mu_k(D_k) \cdot D_k \cdot \omega_k}{\sum_{k=1}^{N_c} \mathbb{1}_k \cdot \mu_k(D_k) \cdot \omega_k} \right|_{i\text{-}th\ building} - D_G^{obs}(i) \right)^2 \tag{15}$$

The optimal values of the weights are then solution of the minimization problem expressed as:

$$\frac{\partial^2}{\partial \omega_k} = 0\ ,\ \forall\ k = 1,\ldots,N_c \tag{16}$$

4.2. Optimization process

It should be noted that the objective function to be minimized has a complex form, which convexity cannot be demonstrated. Therefore, there is no evidence of unicity of the solutions. Several iterative minimization methods can then be adopted in order to reach the global minima of the objective function.

Many heuristic optimization approaches have been tested with proven efficiency, such as the Genetic Algorithms, the Particle Swarm [29] and the Direct Search [30] methods. As the Genetic Algorithms method has shown both efficiency and easy use [31,32], and as is embedded in MatLab, it has been adopted in the present study [33].

5. Application and numerical example

5.1. Description of the database

Since the purpose of the present approach is to provide an automatic processing of a post-earthquake assessment methodology to derive global damage levels, the involved parameters (see Fig. 1) during the processing vary according to the assessment methodology itself, other parameters may be included in case of other application. Therefore, and in order to illustrate the approach, the standard evaluation form used in Algeria is considered [20] to train and validate the proposed approach; a database collected during a real post-earthquake evaluation campaign in Algeria is considered. This assessment of post-earthquake damage is based on visual inspection by trained technical staff where these inspectors are qualified engineers and experts from the National Earthquake Engineering Research Center (CGS, Algeria) and the Constructions Technical Control offices (CTC, Algeria).

Actually, on May 21st, 2003, an earthquake occurred in Boumerdes *(located 45 km east of the capital Algiers, Algeria)* with magnitude Mw = 6.8. This earthquake caused more than 2300 death and tens of thousands of damaged constructions in large areas, multiple teams of experts were dispatched to assess the damaged buildings where the conducted post-earthquake survey covered about 100,000 buildings [34], extracted samples (evaluation forms) from the survey are used to build the adopted database in this study with more than 27,000 included buildings. The evaluation forms are collected near the hypocentral zone in Boumerdes city from the same affected region and under the same seismic intensity (see Appendix A).

The database contains various structural typologies of buildings according to their lateral bracing systems: unreinforced masonry

Table 4
Distribution of buildings according to their typology and damage levels.

Type	Damage level (Category)					Total	%
	D_1 (None)	D_2 (Slight)	D_3 (Moderate)	D_4 (Severe)	D_5 (Collapse)		
RC1	62	9823	2883	1091	355	14,214	51.93
RC2	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	6795	3090	1657	27,371	100
%	0.26	57.57	24.83	11.29	6.05	100	

structures (URM), reinforced concrete framed structures (RC1), reinforced concrete shear walls structures (RC2) and steel structures (S), see Table 4. Buildings classification is adopted from well-known methodologies such as the HAZUS methodology [35] which was adopted in previous studies for the Algerian buildings typologies [19,36]. The database was selected with the assumption that the evaluation forms are accurate and properly filled out. The governing parameters in this study (i.e. "Structural" components and "Non-structural" components) are selected according to their availability in the database, whereas other parameters in the adopted evaluation form (e.g., soil problems around the structure…) have been ignored and therefore the related samples were excluded from the database due to lack of enough samples, such parameters are obviously important but they were also ignored in previous studies [19,21] due to similar reasons. For this, it can be said that the quality of the selected database could affect the quality of the theoretical outcomes of the automatic processing.

5.2. Calibration and comparison

In order to examine the performance of the proposed methodology, the adopted database is divided randomly into two datasets to train (model calibration) and validate (model validation) the proposed approach:

The training dataset which represents 70% of the entire data (19,161 samples) is used to perform the iterative optimization process in order to obtain the optimal fuzzy rule weights ω_k by minimizing the objective function which is the mean square error χ^2, see Eq. (14), the optimization process in this paper is based on Genetic Algorithms where best obtained value of the objective function is $\chi^2 = 0.17$. Obviously, the fuzzy rule weights' values result from a heuristic optimization processes and they may correspond to a local rather than a global minimum of the objective function χ^2. Still, several optimization processes have been performed and the fuzzy rule weights' values were similar though slightly different in each optimization process.

The obtained fuzzy rule weights' values of the groups (i.e.: *Group 1*, *Group 2* and *Group 1–2*) are represented in Figs. 4–6 respectively. For the first sub-fuzzy system (*Group 1: "Structural damage level"*) which provides a structural damage level D_S^*, the rule weights are clearly ascending from D_1 to D_5, where D_5 damage level in every input's variable has the higher value. Also, the inputs' variables have similar relative importance since the weights' values are fairly similar. Also, D_3, D_4 and D_5 show high values for all structural components in comparison to D_1 and D_2, which are extremely low.

For the second sub fuzzy system (*Group 2: "Non-structural damage level"*) which provides a non-structural damage level D_{nS}^*, the rule weights vary from one input variable to another. Actually, there is no clear relation between the inputs. This may be due to the fact that the non-structural components have less influence than the structural components in the case of the Algerian post-earthquake damage assessment methodology. Additionally, during multiple optimization process, the non-structural weights have greatly varied in comparison to the structural parts. This may be explained by their poor influence on the global damage level since the performance of the model was not significantly affected by their changes.

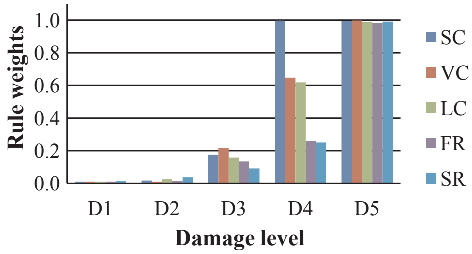

Fig. 4. Fuzzy rule weights ω_k of Group 1: "Structural damage level".

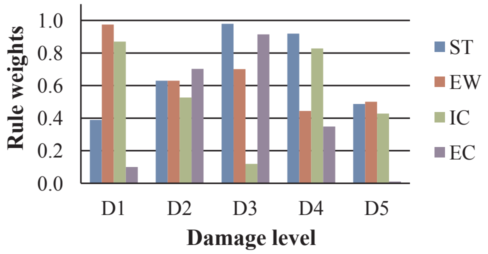

Fig. 5. Fuzzy rule weights ω_k of Group 2: "Non-structural damage level".

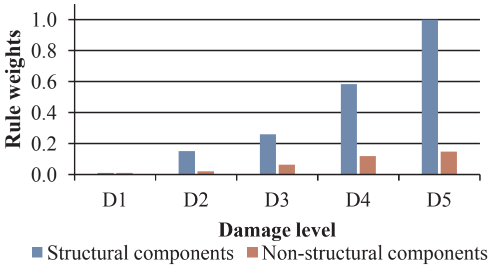

Fig. 6. Fuzzy rule weights ω_k of Group 1–2: "Global damage level".

Finally, for the final fuzzy system (*Group 1–2: "Global damage level"*), the rule weights are in an ascending order from D_1 to D_5 for both structural and non-structural components. Also, a clear shift can be observed for each damage level between the two inputs; structural damage levels have always higher weights in comparison to non-structural damage levels. This result is in accordance with the fact that the structural components are considered as having more influence than the non-structural components regarding the safety during post-earthquake damage assessments. Additionally, by comparing each level of damage of structural and non-structural components, higher damage levels in non-structural components have been noticed to have higher weights compared to lower levels in structural components. This can be explained by the fact that the expected repair cost is also influenced by the non-structural components damage: the higher the non-structural damage level, the higher repair cost and the higher global building damage level.

The validation dataset which represents 30% of the entire data (8210 samples) is used to validate the obtained weights ω_k in order to evaluate the accuracy of the proposed model. During the validation stage, the outputs of the model D_G^* (theoretical global damage levels) are compared to those reported by the inspectors D_G^{obs} (real global damage levels). Since all damage levels in the database are coded as integer values ranging from 1 (D_1) up to 5 (D_5). Conversion of output's values (i.e., numerical values) into quantitative terms (i.e., damage and safety levels) can be achieved by assiging an effective range for each damage and safety level, see Fig. 7.

The obtained comparison results for the training stage and the validation stage are shown in Fig. 8**.** The proposed approach shows a high performance (90% of accordance) during the training and the validation phases and it is able to predict correctly the global damage level. The confusion matrices [37] describe thoughtfully the performance of the approach for each damage level; each diagonal cell represents the well-predicted damage levels, whereas the off-diagonal values represent

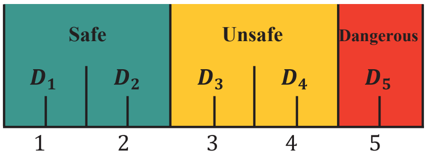

Fig. 7. Effective range for each damage category.

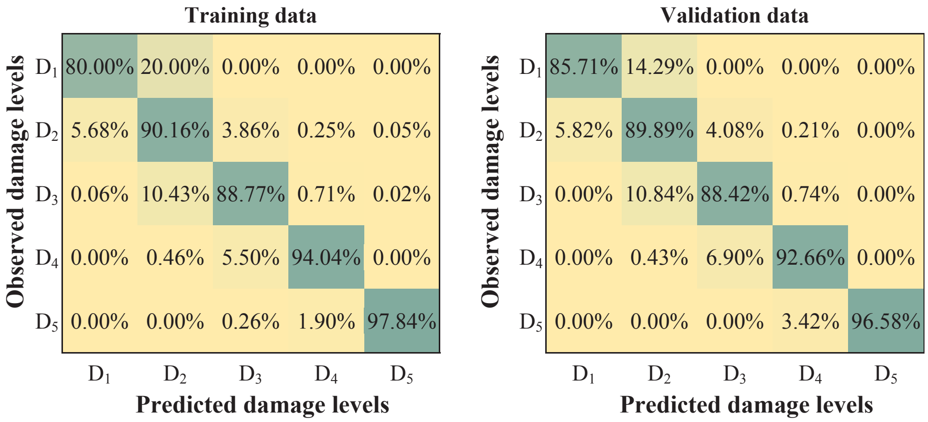

Fig. 8. Confusion matrices for the training and the validation data.

Table 5
Performance of the proposed approach using all data.

Type	D1 (None)			D2 (Slight)			D3 (moderate)			D4 (severe)			D5 (collapse)			Total accuracy (%)
	D_G^{obs}	D_G^*	(%)	D_G^{obs}	D_G^*	(%)	D_G^{obs}	D_G^*	(%)	D_G^{obs}	D_G^*	(%)	D_G^{obs}	D_G^*	(%)	
RC1	62	51	82.26%	9823	8431	85.83%	2883	2311	80.16%	1091	964	88.36%	355	347	97.75%	86.87%
RC2	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	3559	96.37%	1921	1869	97.29%	1288	1256	97.52%	92.79%
Total	71	58	81.69%	15,758	14,194	90.07%	6795	6025	88.67%	3090	2893	93.62%	1657	1615	97.47%	90.30%

Table 6
Comparison between theoretical results and those proposed by inspectors.

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^*	Model decision	D_G^{Obs}	Inspector 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*

the erroneously predicted damage levels. There is, however, a slight decrease in performance for the first damage level (D_1: No damage): this may be due to the small number of buildings with such damage level (D_1: No damage) in the database (0.26% of the database).

Table 5 shows a comparison between the number of assigned buildings in each damage level by inspectors and by the fuzzy model for each structural typology, the accuracy results show that the model is in good accordance with the inspectors reports for each structural typology. However, a slight decrease in performance for RC2 buildings is observed which may be due to the small number of RC2 buildings in the database.

Additionally, the model was able to derive damage levels specific to the:

- "Structural body" as a whole which corresponds to the "Structural components" effect. The structural damage D_S^* is obtained by adopting Eq. (10) to assess the structural components' (i.e.: SC, VC, LC, FR, SR), see Table 6.
- "Non-structural body" as a whole which corresponds to the "Non-structural or Secondary components" effect. The non-structural damage D_{nS}^* is obtained by adopting Eq. (10) to assess the non-structural components' (i.e.: ST, EW, IC, EC), see Table 6.

These specific "Bodies damage" were not included in the original evaluation form. This new possibility provided by the methodology can then be considered as an improvement of the post-earthquake damage evaluation process. Some extracted examples from the database are presented in Table 6, it can be seen that the theoretical global damages levels are in accordance with the proposed damages levels by inspectors as well as the adopted decisions in most cases.

Finlay, adopting weighted fuzzy rules is justified by its simplicity and its performance. As discussed previously, the present model required normally 4181 ($=5^5 + 4^5 + 2^5$) fuzzy rules in order to cover all possibilities using the traditional way. Since not all these combinations are feasible, examining and selecting significant rules to reduce their number is time and effort consuming. Instead, a very small number of rules is obtained using weighted fuzzy rules. The model is built using 55 ($=5 \times 5 + 4 \times 5 + 2 \times 5$) fuzzy rules, which represents only 1.32% of the former number of rules. The proposed approach can be applied efficiently in automatic processing of buildings assessment procedures, as it provides a simple and accurate way to build fuzzy systems in which the development and the definition of the fuzzy sets, input and output variables, as well as the fuzzy rules and their weights, is easy to implement.

6. Conclusions

When dealing with post-earthquake damage, the assessment of buildings' damage is a delicate task. Damaged buildings must be evaluated quickly and rigorously. After major earthquakes, inspectors face always difficulties to assess damaged buildings and to derive accurate global damage levels and non-expert inspectors are often involved which can lead to misclassification of real damage level. To overcome these weaknesses, expert systems are used to help inspectors during the assessment tasks. The present paper presented an automatic processing methodology to help inspectors during the assessment of post-earthquake damage. The proposed methodology estimates the global damage level of the buildings by considering even imprecise, uncertain or incomplete information. It relies on the damage levels observed on each of the "Structural components" (columns, beams, walls, slabs, *etc*.) and the "Non-structural components" (staircases, separation walls, facade, balconies, *etc*.).

The proposed methodology is based on fuzzy logic and relevant weighted fuzzy rules so that it minimizes the number of fuzzy rules which simplifies the development of fuzzy systems. The fuzzy rule weight represents the strength of the rule and expresses the relationships between the components' damage and the global damage level.

The approach presented in this paper considers three fuzzy systems "*Groups*". The first sub fuzzy system "*Group 1*" evaluates five parameters as structural governing parameters and provides a "Structural" damage level. The second sub fuzzy system "*Group 2*" evaluates four parameters as non-structural governing parameters and provides a "Non-structural" damage level. Both structural and non-structural damage levels provided by these sub fuzzy systems are not included in the original form and they can be considered as an improvement of the post-earthquake damage evaluation process. The third fuzzy system "*Group 1-2*" relies on the previous "Structural" and "Non-structural" damage levels to derive the global damage level. Each parameter is associated to five weighed fuzzy rules which represent the intensity of the observed damage, which range from "D_1: No damage" up to "D_5: Collapse". For illustration purposes, a database with more than 27,000 evaluation forms has been collected from a post-earthquake survey (Algeria, Boumerdes earthquake, May 2003, Mw = 6.8).

The fuzzy rule weights are optimized by minimizing an adequate objective function. The results showed that for all parameters, in the first sub fuzzy system "*Group 1*", the rule weights are ascending from D_1 to D_5. Rule weights associated to D_5 damage level have the higher values which refer to the ascending gravity of damage levels. Furthermore, the variables have similar relative importance; and the D_3, D_4 and D_5 damage levels show high values for all "Structural" components in comparison to D_1 and D_2. In the second sub fuzzy system "*Group 2*", there is no clear relation between the weights of the associated fuzzy rules and their values. They seem to have low influence on the global damage level. Finally, in third fuzzy system "*Group 1-2*", the rule weights are ascending from D_1 to D_5 for both structural and non-structural damage levels and a clear shift is observed between the values of the two inputs' variables. The structural components have an obvious higher influence on the global damage value in comparison to non-structural components.

For the case study, the performance of the proposed methodology is tested by comparing the theoretical damage levels with real observed damage levels derived from the collected database. The results show a high performance with 90% of global accordance. The approach demonstrates its ability to predict the appropriate damage level in most cases and the misclassified cases were generally in the immediate close lower or upper damage level. Furthermore, the adopted method reduces the number of fuzzy rules to 55, the lower is the number of rules, the less time consuming will be the development and the computation effort.

On the other hand, improvements can always be suggested and applied to enhance the performance of the proposed approach. More calibration is required since the approach has been calibrated using a database based on only one assessment methodology. Thereby, a validation with different databases and assessment methodologies could confirm the obtained rule weights and clarify more the relationships between the components' damage and the global level of damage of the building.

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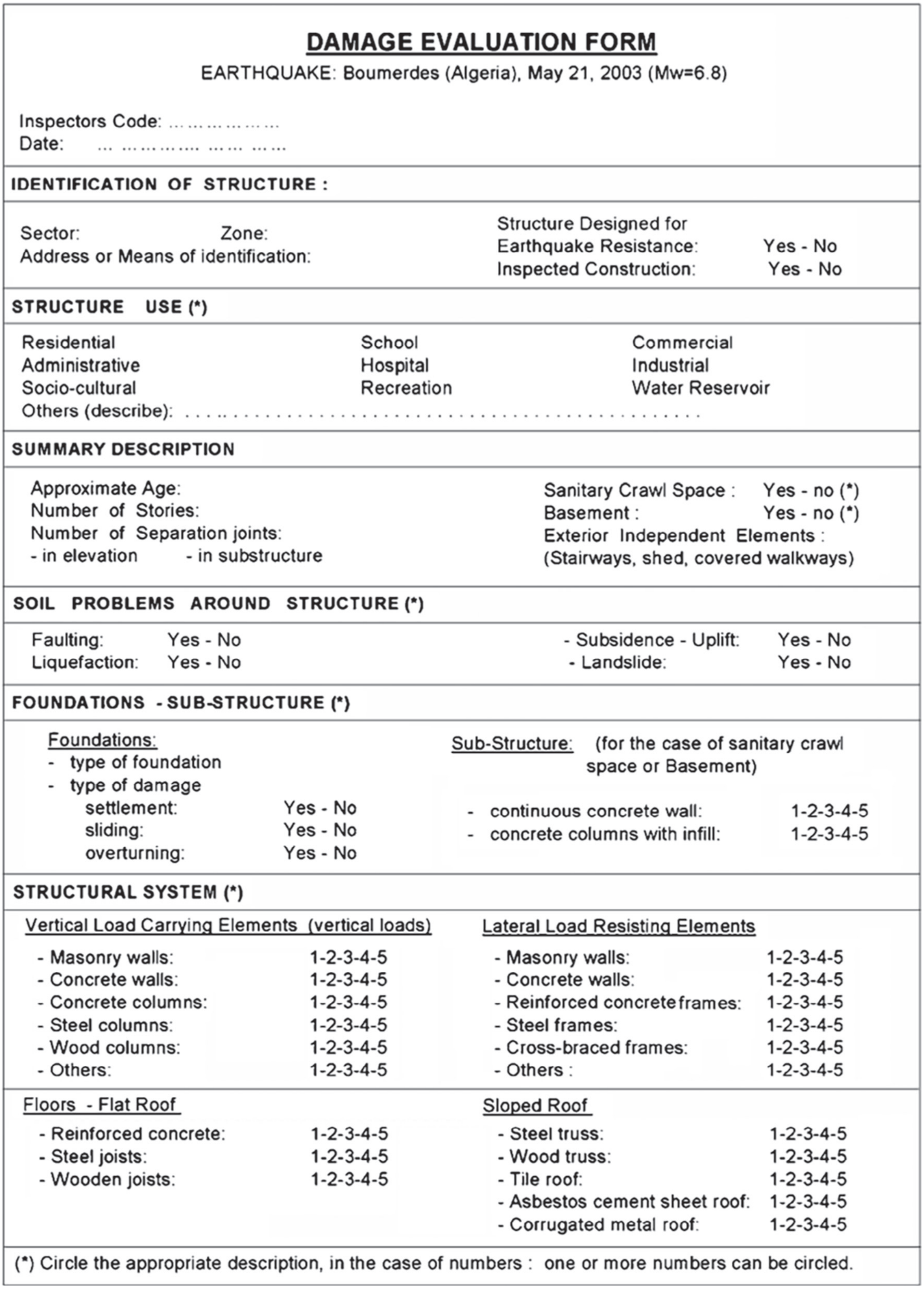
Appendix A. Post-earthquake damage evaluation form [20]

The evaluation form in use in Algeria for post-earthquake disaster evaluation of building damage is summarized in Fig. A.1.



DAMAGE EVALUATION FORM

EARTHQUAKE: Boumerdes (Algeria), May 21, 2003 (Mw=6.8)

Inspectors Code: ………………
Date: … ………… …… ……

IDENTIFICATION OF STRUCTURE :

Sector: Zone:
Address or Means of identification:

Structure Designed for Earthquake Resistance: Yes - No
Inspected Construction: Yes - No

STRUCTURE USE (*)

- Residential
- Administrative
- Socio-cultural
- School
- Hospital
- Recreation
- Commercial
- Industrial
- Water Reservoir
- Others (describe): . . . .

SUMMARY DESCRIPTION

Approximate Age:
Number of Stories:
Number of Separation joints:
- in elevation - in substructure

Sanitary Crawl Space : Yes - no (*)
Basement : Yes - no (*)
Exterior Independent Elements :
(Stairways, shed, covered walkways)

SOIL PROBLEMS AROUND STRUCTURE (*)

Faulting: Yes - No
Liquefaction: Yes - No
- Subsidence - Uplift: Yes - No
- Landslide: Yes - No

FOUNDATIONS - SUB-STRUCTURE (*)

Foundations:
- type of foundation
- type of damage
  - settlement: Yes - No
  - sliding: Yes - No
  - overturning: Yes - No

Sub-Structure: (for the case of sanitary crawl space or Basement)
- continuous concrete wall: 1-2-3-4-5
- concrete columns with infill: 1-2-3-4-5

STRUCTURAL SYSTEM (*)

Vertical Load Carrying Elements (vertical loads)

- Masonry walls:	1-2-3-4-5
- Concrete walls:	1-2-3-4-5
- Concrete columns:	1-2-3-4-5
- Steel columns:	1-2-3-4-5
- Wood columns:	1-2-3-4-5
- Others:	1-2-3-4-5

Lateral Load Resisting Elements

- Masonry walls:	1-2-3-4-5
- Concrete walls:	1-2-3-4-5
- Reinforced concrete frames:	1-2-3-4-5
- Steel frames:	1-2-3-4-5
- Cross-braced frames:	1-2-3-4-5
- Others :	1-2-3-4-5

Floors - Flat Roof

- Reinforced concrete:	1-2-3-4-5
- Steel joists:	1-2-3-4-5
- Wooden joists:	1-2-3-4-5

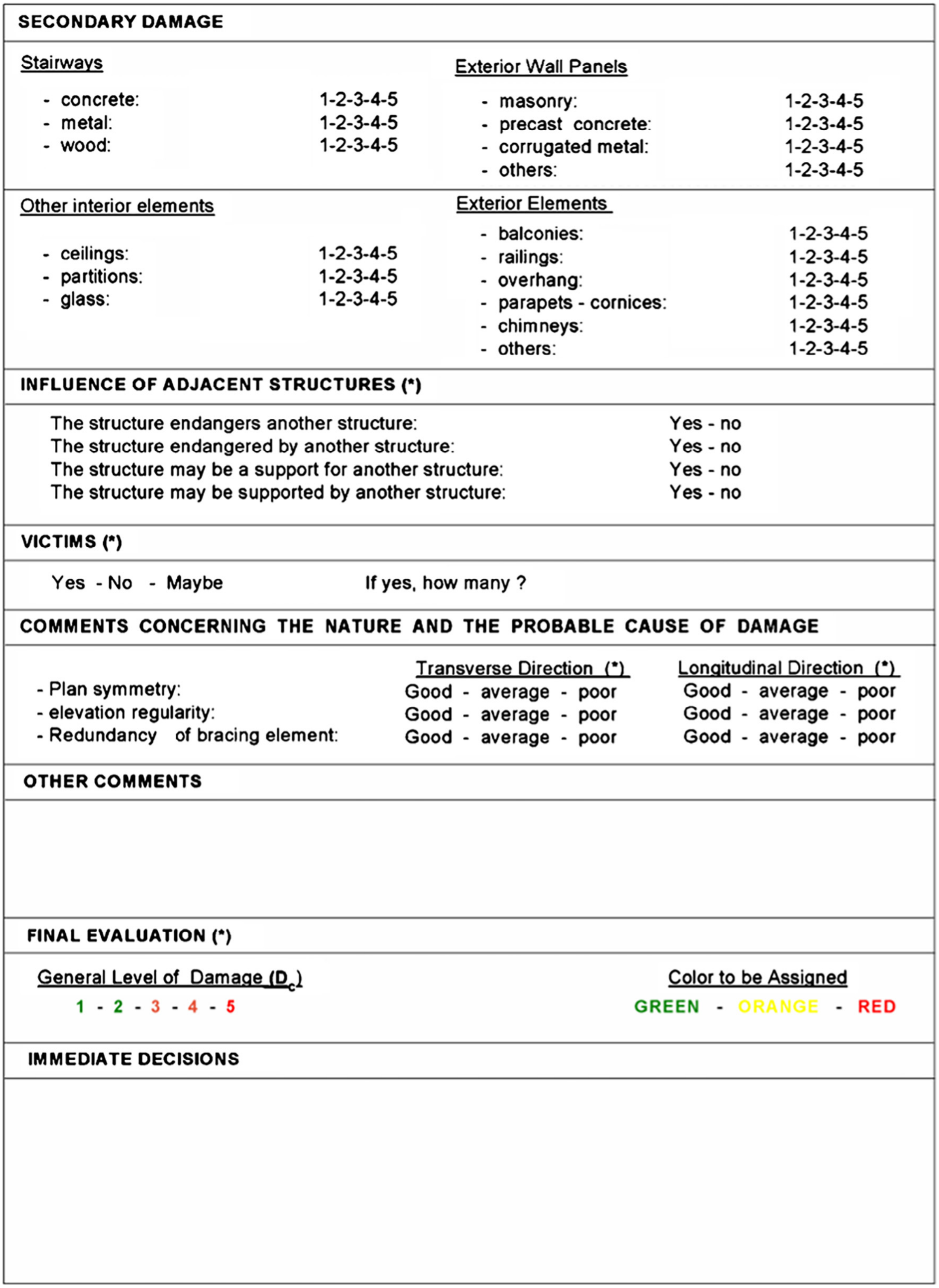
Sloped Roof

- Steel truss:	1-2-3-4-5
- Wood truss:	1-2-3-4-5
- Tile roof:	1-2-3-4-5
- Asbestos cement sheet roof:	1-2-3-4-5
- Corrugated metal roof:	1-2-3-4-5

(*) Circle the appropriate description, in the case of numbers : one or more numbers can be circled.

(a) - First Part of the Evaluation form

Fig. A1. Evaluation form for visual inspection: Parts (a) and (b).



SECONDARY DAMAGE

Stairways		Exterior Wall Panels	
- concrete:	1-2-3-4-5	- masonry:	1-2-3-4-5
- metal:	1-2-3-4-5	- precast concrete:	1-2-3-4-5
- wood:	1-2-3-4-5	- corrugated metal:	1-2-3-4-5
		- others:	1-2-3-4-5
Other interior elements		Exterior Elements	
- ceilings:	1-2-3-4-5	- balconies:	1-2-3-4-5
- partitions:	1-2-3-4-5	- railings:	1-2-3-4-5
- glass:	1-2-3-4-5	- overhang:	1-2-3-4-5
		- parapets - cornices:	1-2-3-4-5
		- chimneys:	1-2-3-4-5
		- others:	1-2-3-4-5

INFLUENCE OF ADJACENT STRUCTURES (*)

The structure endangers another structure:	Yes - no
The structure endangered by another structure:	Yes - no
The structure may be a support for another structure:	Yes - no
The structure may be supported by another structure:	Yes - no

VICTIMS (*)

Yes - No - Maybe If yes, how many ?

COMMENTS CONCERNING THE NATURE AND THE PROBABLE CAUSE OF DAMAGE

	Transverse Direction (*)	Longitudinal Direction (*)
- Plan symmetry:	Good - average - poor	Good - average - poor
- elevation regularity:	Good - average - poor	Good - average - poor
- Redundancy of bracing element:	Good - average - poor	Good - average - poor

OTHER COMMENTS

FINAL EVALUATION (*)

General Level of Damage (D_c)	Color to be Assigned
1 - 2 - 3 - 4 - 5	GREEN - ORANGE - RED

IMMEDIATE DECISIONS

(b) - Second Part of the Evaluation form

Fig. A1. (*continued*)

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