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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.

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