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EARTHQUAKE DAMAGE ASSESSMENT OF REINFORCED CONCRETE MEMBERS USING AN EXPERT SYSTEM

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ABSTRACT

The assessment of damage of reinforced concrete (RC) structural elements relies on the engineering judgment of the person in charge of the inspection and evaluation. A rule-based prototype expert system was developed to assist a structural engineer in the assessment of postearthquake damage to RC structural elements, providing guidance for inspection, criteria for evaluation and recommending courses of action to take afterwards. This expert system, called DASE, identifies the most likely failure modes that may be developed by the RC columns or beams of a damaged building, determines the severity of damage and suggests rehabilitation procedures or tests, to maintain an acceptable local safety level. Also, floor damage classification and restoration guidelines are provided, assuming that all the structural components in a building's floor have been inspected. The Analytic Hierarchy Process has been implemented as the framework to determine the severity of damage since it allows judgments and personal values to be represented systematically and rationally. DASE provides graphics that customize the user interface and an explanation facility. The knowledge incorporated into its knowledge base consists primarily of scattered, yet fairly structured, documented knowledge found through literature research.

KEYWORDS

Damage assessment; expert system; reinforced concrete elements; engineering judgment; inspection.

INTRODUCTION

After an earthquake strikes, inspection and assessment of the state of damage to building structures are imperative and critical for evaluating their safety and determining emergency and long term actions required to reduce the risk of collapse of those structures that remain standing, and exhibit need for repair or strengthening. In a state of emergency of this type, personnel shortcomings arise leading to a search for additional (maybe unqualified) manpower. In such situations, the time and cost of training become critical, and the lack of them may or does affect substantially the effectiveness of the inspection programs. In addition, exhaustion and other symptoms of emotional and physical fatigue, can impact greatly the ability to reason and make judgements. The assessment and repair of existing structures that may or may not be damaged entirely is a complex engineering decision-making task. Various people may interpret visual inspection data and make engineering judgements differently according to their knowledge of the subject, either through formal training or from experience. These facts are strong reasons for developing a systematic approach that can provide rational conclusions, and simulate the judgment of an expert. The technology of artificial intelligence provides a feasible and practical approach by supporting the decision making process through the development of an expert system.

In the past, several expert systems related to damage assessment of structures have been developed (see Melchor-Lucero and Ferregut (1995)), yet they only provide estimates of the level of damage of a structure based on global observation of the structural system, failing to recognize the influence that each structural element has on the global safety of the structure.

Methodologies have been developed to conduct forensic investigations and structural evaluations (KMU, 1984; Yao, 1984; ASCE, 1989; ASCE, 1990; ATC, 1989; Ohkubo, 1990), addressing issues that cover data collection for spatial analysis and planning, reliability-based safety evaluation, forensic engineering training, inspection, evaluation and restoration guidelines. Other authors have attempted to rationalize and mathematically model damage in structures, leading to the development of damage measures for RC members. Although, these methodologies and mathematical models provide well-defined and structured approaches to assess damage, situations are encountered, during field inspections, where its very difficult, if not impossible, to follow them without letting the inspector have considerable use of judgement. As a result, global damage assessment methods could lead to very conservative conclusions regarding the safety level of the structures. A more accurate way of assessing damage to a building is to conduct a detailed assessment, on an element by element basis, and then aggregate these results into a single global damage estimate.

Therefore, the expert system DASE (Damage Assessment of Structural Elements) was developed to provide a rational computerized approach for the assessment of postearthquake structural damage to RC elements. The system: 1) analyzes distress conditions to determine and rank qualitatively the possible modes of failure of RC structural elements (limited to beams and columns); 2) assigns qualitatively a level of damage to the element using scalar indices that represent the severity of each of the possible distress conditions that can be present on the element; 3) determines whether a damaged member should be rehabilitated for future use and suggests alternative methods of repair or restoration; 4) qualitatively classifies floor damage in a global sense, considering the individual assessments of each structural element; and 5) explains "why" a specific piece of information is needed, and explains "how" a conclusion was derived. The assessment process is judgmental, based upon visual inspection of the physical condition of the structural element, and the damage levels are described qualitatively (e.g., none, slight, severe, etc.). The system is intended as an aide to a structural engineer with an expected academic background equivalent to a bachelor's degree with little or no knowledge of expert systems, allowing the engineer to have the final decision.

SYSTEM STRUCTURE AND METHODOLOGY

The expert system DASE has three major modules:
Module I. Damage assessment of concrete structural elements, where possible failure modes are determined and ranked and the damage condition is assessed.
Module II. Rehabilitation methods for damaged elements, where methods of repair or testing procedures are suggested, and
Module III. Floor damage classification, where the floor damage is classified as a function of the damage to the structural elements, and restoration techniques are proposed for the overall building.

Figure 1 illustrates the general flowchart of this expert system showing the main processing blocks of each module, and their interdependence.

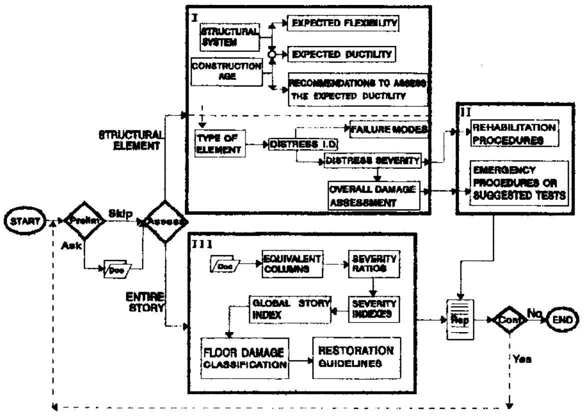

Fig. 1. DASE's knowledge base modules and general flowchart (after Melchor-Lucero and Ferregut (1995)).

Module I. Expected Behavior of the Building and Failure Mode Determination of the Element

The first blocks in Module I qualitatively determine the expected flexibility and the expected ductility performance of the building being inspected according to: the type of structural system; the code followed for its design; or the identification of the materials used during construction. If data about materials is uncertain or unknown, the system provides recommendations to assess the expected flexibility and ductility. Three types of structural systems are considered: flat or waffle slabs and columns, frames braced with shear walls or X type bracing and frames not braced at all. The system may be considered either flexible or rigid. Also, from the ductility point of view, the system may be ductile or partially ductile.

A building may be classified according to the code used for its original design into buildings designed before 1970 and buildings designed after that year. The reference year 1970 is chosen because during the seventies, design codes changed substantially (ATC, 1989; ICA 1988) to consider the ductile behavior of the structures more explicitly. Therefore, structures designed after 1970 are expected to perform in a more ductile manner than those designed before that year. If the design code is unknown, ductility can be assessed through the determination of the materials used in the construction. Construction materials are important age indicators for earthquake resistance (ATC, 1989). Three cases are considered: straight sheathing form marks indicate older construction, plywood form marks are evidence of recent construction and unknown marks suggest uncertain construction age. Confidence factors are assigned to the expected structural behavior, to reflect the degree of certainty or likelihood of the experts' answers or conclusions.

Other blocks in Module I request information about several possible postearthquake distress conditions (cracking, spalling, crushing, deformations or others) that may be observed in the structural elements. Two types of structural elements are considered by this system: Columns and Beams. Both are assumed to be prismatic with rectangular cross sections. This information is further processed using pattern recognition techniques to identify failure modes of the structural elements, such as flexure, shear or combined failure, or others. Possible patterns, locations, and the appearance of the distress conditions are combined in order to perform pattern recognition to identify the failure modes. Confidence factors are assigned to each failure mode. Furthermore, the ductile or brittle behavior of the individual elements is assessed.

Module I. Damage Assessment Methodology

In addition to determining the failure mode of the element, the severity of the damage is assessed according to the following assumptions. (1) Damage assessment depends on the type of structural element and the severity of the distress conditions; (2) a scale of up to six levels is used to classify the severity of damage in accordance to ACI's criteria (ACI, 1968; ACI, 1986) and to Japanese techniques for postearthquake damage inspection (Ohkubo, 1990); (3) a verbal descriptor and a damage index are associated to each level of severity; (4) damage assessment may be performed from different standpoints such as serviceability, structural safety, aesthetics, cost of repairs and/or others.

Since damage assessment depends on the results of visual inspection and qualitative factors, the Analytical Hierarchy Process (AHP) (Saaty, 1982) was implemented to logically process that information. The AHP distinguishes three principles that are applied when solving problems by explicit logic analysis: (1) the construction of hierarchies, (2) the establishment of priorities and (3) the consistency in logic.

The damage assessment process can be represented as a hierarchy as shown in Fig. 2. The top level of the hierarchy is the damage assessment of the structural element which is the final objective. The next level represents the possible standpoints (serviceability, safety, aesthetics, etc.) from which to judge the importance of the distress conditions (cracking, spalling, et cetera), which is the subsequent level of the hierarchy. The lower level shows the set of distress factors that may affect the distress conditions.

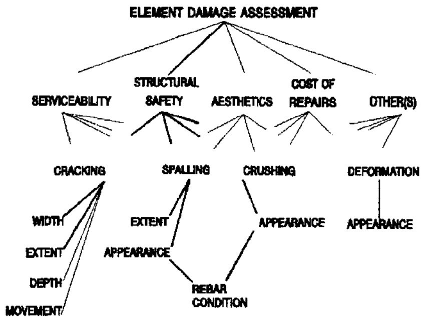

Fig. 2. DASE's hierarchy levels for damage assessment applying the AHP (after Melchor-Lucero and Ferregut (1995)).

Once the factors that influence the outcome of the element damage assessment are identified, a priority setting process defines whether some of them are dominant and others sufficiently insignificant that they may be ignored. This is done by comparing the elements in pairs against a given criterion. For pairwise comparisons, a matrix is the preferred form. Saaty (1982) explains the procedure to follow and defines the scale (from 1 through 9) assigned to judgements in comparing pairs of like elements in each level of a hierarchy against a criterion in the next higher level, being one the lowest intensity of importance and nine the highest, meaning equal and absolute importance, respectively.

The AHP method also measures the overall consistency of judgements by means of a consistency ratio whose value should be 10 percent or less. If it is more than 10 percent, the judgements may be somewhat random and, perhaps, should be revised. An example of a consistency check is given when determining the structural element' damage assessment. The following section illustrates the application of the AHP methodology to the assessment of damage to the cracking condition.

Damage Assessment of the Cracking Condition

When assessing the severity of the cracking condition of a damaged structural element, several factors can be considered. These could be crack width, extent of cracking or crack density (number of cracks per unit area), crack depth, or crack movement (if active) as shown in Fig. 2. These factors can be ranked according to the relative influence they have on the severity of the cracking condition, forming a pairwise comparison matrix. Table 1 illustrates a possible matrix arrangement.

Table 1. Pairwise comparison of crack factors against influence over the cracking condition (after Melchor-Lucero and Ferregut (1995)).

Damaging influence over cracking condition		*(w)*	*(d)*	*(dp)*	*(m)*	(.)	(..)
crack width	(*w*)	1					
crack density	(*d*)		1				
crack depth	(*dp*)			1			
crack movement	(*m*)				1		
other	(.)					1	
other	(..)						1

When comparing one factor in the matrix with itself, e.g. crack depth with crack depth, the comparison value must be one. Therefore the diagonal of the matrix is always filled with ones. The element in the left-hand column of the matrix is always compared with the element in the top row of the matrix. When performing the opposite comparison, use the reciprocal value.

In this project the authors simplified the problem to only two factors: 1) the maximum crack width encountered (regardless of loading conditions, time effects, and active movement) and 2) the crack density (regardless of the crack widths encountered throughout the concrete surface). Each factor is expressed in terms of an index that associates a certain distress condition of the factor being assessed to a severity descriptor. Then a cracking condition index can be computed as:

$$C_k = W_w C_w + W_d C_d \tag{1}$$

where: C_k is the cracking condition index; C_w is the crack width index; C_d is the crack density index; and $W_i = v_i/\Sigma(v_i)$ is the weight of each crack factor, where v_i is the "importance factor" (assigned by experts), through the pairwise comparison of the AHP. The weights reflect the degree of importance of each crack factor has over the cracking condition.

Table 2 illustrates maximum crack width scenarios considered when assessing the crack width damage on the surface of the concrete. It also shows the associated "crack width indexes" and "crack width severity descriptors". The selected crack width ranges are based on those proposed by Ohkubo (1990). As the width of the crack increases so does its severity because it increases the possibility that rebar may corrode or that the rebar has yielded.

A similar table was developed for crack density scenarios (based on (ACI,1986)), assuming that as cracking becomes denser its severity increases because the potential for rebar corrosion is higher to a greater extent (Melchor-Lucero, 1993).

To determine the proposed importance factors (v_i) for cracking, the following assumptions were made:
1). when crack width severity is assessed as 'very severe', its influence over the overall cracking condition is maximum or absolute regardless of the crack density severity; 2). when crack width severity is assessed as 'slight', severity of crack density governs; 3). when crack width severity is assessed with any other descriptor the AHP is used; and 4). the importance factors (v_i) for cracking are independent of the structural element under consideration.

From the list above only case 3 requires the AHP approach. The comparison values were determined by answering the question: How much more influence does crack width have compared to crack density over the cracking condition, when crack width damage is assessed as intermediate?

Table 2. Crack width scenarios with associated index (C_w) and severity descriptor. (after Melchor-Lucero and Ferregut (1995)).

Maximum observed crack width (mm)	C_w	Severity descriptor
No cracking	0	None
width ≤ 0.2	1	Slight
0.2 < width ≤ 1.0	2.5	Moderate
1.0 < width ≤ 2.0	4	Severe
2.0 < width	5	Very severe

The authors considered that crack width is four times more influential in the overall cracking condition than crack density. Therefore, reciprocally, crack density has only one quarter of the influence of the crack width in the overall cracking condition. Their answer to this question was based on subjective judgement and understanding of the behavioral mechanics of cracked concrete elements. Table 3 shows the importance factors and weights for the cracking condition. These are the factors used in equation (1) to compute the cracking condition index.

Table 3. Importance factors and weights for "Cracking condition". Case I) Crack width severity is very severe. Case II) Crack width severity is slight. Case III) Crack width severity is neither very severe nor slight. (after Melchor-Lucero and Ferregut (1995)).

CASE	Importance factors		Weights	
	Crack width	Crack density	Crack width	Crack density
	v_{cw}	v_d	W_{cw}	W_d
I	1	0	1	0
II	0	1	0	1
III	4	1	4/5	1/5

Once the cracking condition index is computed, it is associated to a "severity descriptor" as described previously for the crack factors. Confidence factors may be assigned to each severity criterion. In this prototype, however, a value of 9/10 was given to each of them. Similar exercises were conducted to determine the indexes for the other distress conditions namely spalling, crushing and deformation damage (Melchor-Lucero, 1993).

Structural Element Overall Damage Assessment

The assessment of damage of a structural element depends on the type of element and the distress conditions, namely cracking, spalling, crushing and deformation, whose severity may be assessed from the observation of a number of distress factors, such as crack width, spall extent, crush appearance, rebar condition and others.

Once the distress condition indexes and their respective severity descriptors have been determined, the overall damage index is obtained by aggregating these assessments according to the following formula,

$$D = W_{ck}C_k + W_s S + W_{ch}C_h + W_{df}D_f \tag{2}$$

where: D is the overall damage index for the structural element; C_k is the cracking condition index; S is the spalling condition index; C_h is the crushing condition index; D_f is the deformation index, and W_i is the weight for each distress condition.

To obtain the weights (W_i) for each distress condition the following simplifications were assumed: 1). The importance factors (v_i) for each distress condition are obtained separately for each type of structural element, considering its importance within the load paths; 2). Using the AHP, the distress conditions are compared to determine their influence on the overall element' damage from the structural safety standpoint (see Fig. 2); 3). The values of the importance factors are influenced by the magnitude of the distress conditions. Thus also making the weights dependent on these magnitudes. To simplify the process, the importance factors were determined assuming that all distress conditions were "very severe" regardless of the failure mode developed; 4). If one or more distress conditions do not develop, they should not have an influence on the overall damage assessment. Therefore they are not considered in the calculation of the overall damage index. The process is described for a beam in the following paragraphs.

Table 4 shows the ranking of the distress conditions for a beam, with respect to the "structural safety" standpoint, according to the authors' judgements.

Table 4. Pairwise comparison of the distress conditions against the damaging influence to the structural safety of a Beam (when all distress conditions are developed) (after Melchor-Lucero and Ferregut (1995)).

Structural Safety		*(ck)*	*(s)*	*(ch)*	*(df)*
cracking	*(ck)*	1	1	1/3	1/2
spalling	*(s)*	1	1	1/3	1/2
crushing	*(ch)*	3	3	1	2
deformation	*(df)*	2	2	1/2	1

To evaluate the consistency in the judgements shown in table 4, the matrix is normalized and mathematically manipulated to determine a parameter λ_{max} (Saaty, 1982), which has a value of 4.014 for this case. Afterwards, the consistency index (CI) of the matrix is determined by subtracting from λ_{max} the size of the matrix and averaging the total, obtaining a value of 0.007. To determine the consistency ratio, the consistency index is divided by a random consistency index proposed by Saaty (1982). For a matrix size 4, the random CI is 0.90. Therefore the consistency ratio (CR) in this case is CR= 0.007/0.90 = 0.00078.

The value of the consistency ratio should be 10 percent or less (Saaty, 1982). In this case it approaches zero indicating that there is very good consistency in the judgements. Therefore, no changes are needed in the original matrix of table 4. The final values for the overall importance factors (v_i) for a beam were chosen from those in the second column of the original beam matrix (see table 4).

The same procedure was followed to derive the weights for a column, with only a few variations. When considering the pairwise comparison for a column, the deformation condition (buckling) was left out and assessed independently.

Finally, table 5 shows the importance factors (v_i) of each distress condition, according to the type of structural element where the distress develops, and table 6 shows the overall damage descriptors related to different overall damage index intervals.

Table 5. Importance factors (v_i) for each distress condition.
Case I) No distress conditions developed. Case II) Distress conditions in a Beam.
Case III) Distress conditions developed in a Column.
(after Melchor-Lucero and Ferregut (1995)).

Case	Cracking v_{ck}	Spalling v_s	Crush v_{ch}	Deformation v_{df}
I	0	0	0	0
II	1	1	3	2
III	1	1/2	2	-

Module II. Retrofit Actions for Damaged Elements

Once the element's damage has been assessed, actions to take afterwards are suggested in Module II, as illustrated in Fig. 2. Three types of actions are considered, depending on the assessment: repair, emergency restoration and/or conducting destructive and non-destructive tests.

Repair procedures are suggested depending on the type of element and on the severity of each distress condition. Typical repairs considered in this expert system include: injection of cracks with low or high viscosity epoxy resins, strengthening with steel ties, concrete or steel plate jacketing, epoxy glued steel plates and others. Each option is associated with a confidence factor. Different retrofit measures may be recommended and some of them may even seem to interfere with others. Therefore, the user remains the ultimate decision maker in choosing between the recommended procedures.

Table 6. Damage index (D) and damage descriptor (after Melchor-Lucero and Ferregut (1995)).

Overall damage index	Overall damage descriptor
$D = 0$	Visually undetected
$D \leq 1.0$	Very slight
$1.0 < D \leq 2.5$	Slight
$2.5 < D \leq 3.5$	Moderate
$3.5 < D \leq 4.5$	Severe
$4.5 \leq D$	Very severe

Emergency restoration techniques are determined according to the overall damage assessment, the type of element and the degree of safety required. Emergency actions may include temporary shoring using steel supports, temporary strengthening with steel ties, and others. Tests are also suggested when no structural damage has been detected by visual means or the element is considered undamaged. Tests range from destructive to non-destructive procedures, basically following ACI and ASTM specifications. The tests address the determination of significant characteristics of the concrete and the reinforcement, such as: compressive strength of concrete, yield strength of reinforcement, moisture content in concrete, and presence and extent of corrosion. Also, analytical evaluations and static load tests are suggested to complement the assessment and verify the structural integrity of the building. Most of the information used to produce the rules in this module was acquired from Malhotra (1991). For a listing of relevant papers see Melchor-Lucero and Ferregut (1995).

Module III. Floor Damage Classification and Restoration

Once all the structural components of a floor have been assessed, an entire story damage classification can be performed and restoration guidelines recommended (see Fig. 2). The number of damaged elements are requested and classified according to their damage severity to finally arrive at a global story index. The procedure is based on Japanese criteria (Ohkubo, 1990).

REQUIRED INPUT INFORMATION

When conducting a building inspection with the purpose of using DASE to asses the integrity of the elements in a structure, it is necessary that the inspector collect some basic information that is then used as input to the system. This information can be classified into three groups, depending on the module that is being accessed. When the user accesses Module I the information that is required is: Type of structural system being inspected, type of bracing used in the structure, the code used in the original design and the year of construction or design. This information refers to the overall structural system. The information required at the element level is: Type, location, appearance and magnitude of distress conditions.

Module II does not require any external input information other than that obtained in Module I. However, when the user accesses Module III a different type of information is required. This includes the type, magnitude and number of damaged elements in a given story.

KNOWLEDGE BASE

The knowledge base of the prototype system consists of 176 rules, 30 qualifiers, 172 choices, 61 variables and 21 graphical sketches. As mentioned before, confidence factors are used and assume values between 0 and 10. All possible rules are invoked to arrive to a conclusion, even if unnecessary rules are invoked or unnecessary questions are asked. Knowledge is represented in the form of production rules of the IF - THEN type. Most of the rules implemented in the system have an explanatory note and the reference from where they were derived. Graphical sketches were employed to clarify the input and the conclusions.

Most of the rules derived for DASE were a result of the analysis of documented knowledge through literature research and the authors' experience and judgement.

VALIDATION

Validation of the system was conducted with two objectives in mind: 1) to measure the efficiency of the system, in terms of clarity of the questions asked, the conclusions reached and the explanations provided; and 2) to measure its effectiveness in terms of accuracy, completeness, coverage of the knowledge domain, capacity of the system to be used in a broad range of structural damage situations, and reliability of the conclusions. Validation was conducted through a questionnaire addressing the above criteria. Three professionals, two from academia and one from industry completed the questionnaire. Sometimes, evaluators chose not to answer some of the questions. In general, the validations for the efficiency and effectiveness of the system were satisfactory. Only clarity of explanations and conclusions, breadth of the knowledge domain and generality were rated average by one of the evaluators. Evaluators were also asked to prioritize the potential benefits of the system. In general, the system was viewed as a training tool, time saver and a means to preserve expertise.

CONCLUSIONS

The result of this research has been a rule-based prototype expert system for the assessment of postearthquake structural damage of cast in place concrete components. The Analytic Hierarchy Process (AHP) was implemented as an overall framework to rationalize the damage assessment methodology, due to its great flexibility and similarity with the human thinking process. The knowledge incorporated into DASE's knowledge base is limited mainly to bibliographical references.

In the assessment of the severity of damage in the structural elements, using the (AHP), several simplifications were made: only the structural safety standpoint was used to assess the element's damage; only a limited number of distress factors were considered and their priorities were determined by the authors; simplified confidence factors were assigned by the authors due to the nature of the confidence system selected from the software.

DASE captures and preserves damage assessment expertise of a narrow and well bound domain (structural concrete columns and beams) that can be required in many places at the same time in hazardous situations and that may not be readily available and/or may become very expensive to acquire. It improves the performance of assessing damage providing a consistent methodology (AHP) that can be flexible and adaptable at the same time and enhances the quality of the conclusions or recommendations reached, providing straight forward explanations. Several graphic files were included to customize the user interface, clarifying both, the requested information to be entered as input data, and the conclusions or retrofit procedures suggested by the system.

According to the above, DASE can provide training to novice engineers and disseminate the problem solving skill, which is the purpose for which it was conceived.

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