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DECISIONAL TREES AND FUZZY LOGIC IN THE STRUCTURAL SAFETY ASSESSMENT OF DAMAGED R.C. BUILDINGS

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SUMMARY

The research work presented is focused on the safety assessment of modern R.C. buildings that are either damaged because of the occurrence of external events – such as ground motions – or simply are deteriorated after a number of years of life service because of an "early" aging process. The problem of the durability of R.C. constructions is indeed an acknowledged question and an assessment of their actual safety conditions is widely needed, above all in seismic areas, in order to plan systematic maintenance and inspection programs. The diagnostic process for the evaluation of the safety level of existing buildings is based on a decisional tree in which the data and information collected at each stage are processed and interpreted in order to define the successive step of the procedure. Basically three main stages can be singled out in this flow chart.

Phase A: Preliminary analysis (visual inspection; basic on site testing) aimed at obtaining a coarse and concise appraisal of the apparent health conditions of the structure and defining a rapid mapping of instabilities, damage and vulnerability. In this phase it is possible to ascertain the presence of imminent dangers and promptly suggest the adoption of safety provisions. On the basis of the data acquired, it will be then decided if further and more detailed investigations are needed.

Phase B: More detailed in-depth investigation, including a systematic and complete survey of the damage scenery; experimental and laboratory tests (both destructive and non destructive).

Phase C: Interpretation of the results; formulation of the judgment on the level of damage and reliability; specification of repair and retrofitting interventions needed in order to meet safety law requirements.

In order to manage the diagnostic process just outlined, a *Fuzzy Logic* based algorithm is proposed, which exploits the *fuzzy toolbox* package of MatLab Software. Fuzzy Logic is a versatile tool, particularly suitable for the management of decisional trees involving the processing of data endowed with a "vague" nature (both numerical and qualitative ones), and is naturally able to provide a linguistic, qualitative assessment of the health conditions of the building. The operational algorithm is divided into two phases: Phase A–preliminary investigation; Phase B–in-depth analysis. For each of them a sequence of operations is performed: subsets of data are implemented at each step, fuzzified and then combined in order to obtain an intermediate output. The final result is, at the end of the decision chart, the assessment of the safety level of the structure by means of a qualitative linguistic judgment and a numerical score as well.

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INTRODUCTION

The aim of the research work is to define an effective and feasible method for the damage and safety assessment of existing R.C. buildings. In particular, attention is devoted to the identification of the relevant data on which the structural analyses should be based; the systematization of the investigation protocol; the implementation, management and automatic processing of the available data in order to formulate a concise judgment on the damage state and safety level of the building (in which, besides the different data and variables of the problem, the uncertainty and the error involved are accounted for as well). In order to obtain the information for the static assessment of the structural elements, it is necessary to perform a diagnostic investigation, following a systematic procedure that will progressively proceed into the details of the problem. That will include visual inspections, surveys, experimental testing on site and in laboratory (both destructive and non destructive) aimed at the verification of the hypotheses formulated in the preliminary phases.

From a technical point of view, a lot of appropriate and specific technologies are available that can be employed for supporting these operations: since 1983, the subject has been extensively studied producing a number of technical documents and guidelines, such as the FIP CEB proposals [1, 2]. The relevance that in the last few years has been granted by the international scientific community to the question of the assessment of the residual strength of existing structures is witnessed by the international 1993 I.A.B.S.E. Colloquium on the subject "*Remaining structural capacity*" [3]. The documents produced in that occasion still represents a fundamental reference for the research works devoted to diagnostics and the safety assessment of existing R.C. buildings.

Besides the problems related to the methodological approach for the diagnostic inspections and the related protocols (that is particularly interesting and stimulating both for the professionals and the scholars), a separate and quite complex question is represented by the interpretation of the data and consequent formulation of the final diagnosis about the "health" of the structure. In fact, such a matter heavily involves the uncertainty factors characterizing all the phases of the procedure (shortage/incompleteness of available data; instrumental or human errors during tests and surveys; reliability and intrinsic errors of the chosen structural model or in the calculations; …).

The work that is here presented is specifically focused on these aspects, proposing a fuzzy logic based approach for the management of the diagnostic procedure that has been briefly outlined, and that will be more extensively described in the following sections. Indeed, fuzzy logic is a mathematical tool naturally suitable for formulating a concise, linguistic judgment on the safety conditions of an existing building on the basis of input data (both numerical and qualitative) having a vague nature.

DEGRADATION OF REIFORCED CONCRETE AND STRUCTURAL DIAGNOSTICS

On a scientific and technological standpoint, the knowledge of reinforced concrete as a vulnerable material with respect to the deteriorating action of time is well established, and is widely proved by several RC buildings, whose poor performances are very well known by the professionals. Indeed, during its life, reinforced concrete suffers a quite a few chemical and physical phenomena endangering in a direct or indirect fashion the performance of the construction. Some of them are strictly dependant on human mistakes, other phenomena are basically a natural decay of the material, but can be made worse by the negligence of man.

Actually, we have to manage with an architectural "modern" heritage that is seriously exposed to deterioration phenomena and pathologies endangering the structural and human safety, and indeed the issues of the structural safety assessment, maintenance, and structural rehabilitation of RC structures have become crucial and urgent questions, also from a quantitative point of view, to which all the most recent technical codes and specialist analyses by now dedicate a wide attention.

The diagnostic procedure is a complex and uncertain process, relying on an integrated path of preliminary knowledge, analysis, decision-making and action (architectural interpretation, experimental investigation and testing, analytical modeling, choice of the intervention technique), and the acquisition of reliable data, in most cases, is only achievable by applying time consuming and expensive procedures. On the other side, the dimension and extension of the problem (considering the great number of buildings in danger), would instead require faster and non-invasive diagnostic methods, even at the cost of reducing the accuracy level of the assessment. Actually, if we keep in mind that a priority is generally to identify those situations in which the danger is imminent, or to prescribe the necessity of further investigations, even a coarse appraisal of the safety level of an existing building is often a significant outcome, above all if this is achieved in a short time and causing the minimum damage to the structure.

More detailed and precise analyses will be performed later, if appropriate, when the first coarse screening has pointed out that the structural safety level is lower than a minimum threshold.

In this perspective, it seems reasonable to define proper "diagnostic protocols" (such a definition is intended to include not only the choice of the survey and testing methods, but also the methodology to adopt for the operational procedures and for the data processing) able to provide satisfactory results as quickly as possible and with moderate destructive actions.

While laying the basis for the research work, first of all the operational scheme for the organization of the diagnostic process has been identified. The different working phases to be faced have been singled out, and for each of them the logical and temporal sequence of the individual operations has been specified:

- **Preliminary "quick" knowledge (PHASE A).** In this phase, that is essentially based on visual inspections and on site basic testing, it is possible to point out situations of severe and imminent danger needing a prompt provision, and a judgment about the opportunity of extending the investigation is expressed. It could also happen that the deterioration and damage levels are so low that immediately it is recognized that no further investigation or intervention is needed.
- **Extensive and detailed investigation (PHASE B).** In most cases, the preliminary investigation has to be supplemented and completed with more exhaustive data in order to assess the mechanical consistency of the materials and the extent of the deteriorating phenomena ahead. This phase will obviously require more extensive surveys and will be supported by laboratory and on site experimental testing (applying both destructive and non destructive techniques).
- **Data Processing and interpretation.** Once the on site operations have been accomplished, the collected data must be inventoried and processed, in order to provide the final diagnosis, that is to say, a judgment about the safety level of the building and the damage extent. If appropriate, the rehabilitation measures aimed at guaranteeing the prescribed safety conditions can be outlined.

The diagnostic procedure is based on a decisional tree in which, on the basis of the information acquired and the indication provided by their interpretation it is established the following step to be taken, according to the flow chart shown in figure 1.

Such a hierarchic organization is strictly necessary if we consider that the choices to be made in order to meet the compelling safety requirements depend on a number of additional factors: economic evaluation of the cost and feasibility of the rehabilitation; functional implications involved by the actual use of the building; necessity of inventorying and ranking the emergency grade for the population of buildings, in order to rationalize the available economic resources.

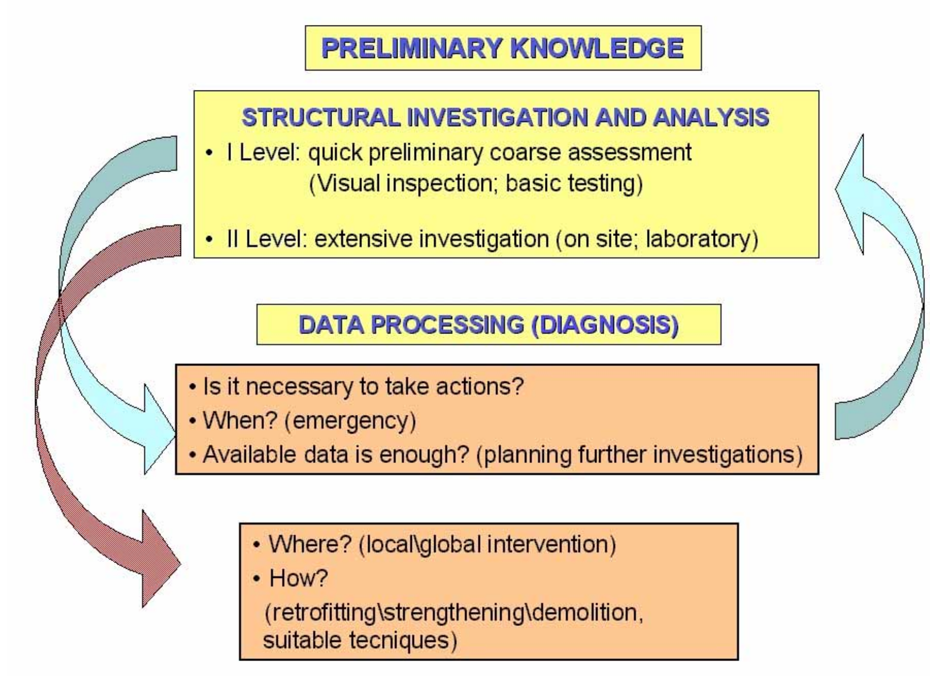

Figure 1: Operational flow chart of the diagnostic protocol.

THE UNCERTAINTIES IN STRUCTURAL SAFETY EVALUATION: APPLICATION OF FUZZY LOGIC THEORY

The probability theory surely represents an important tool for assessing the structural reliability, since it allows to take into account the uncertainty and randomness of the data involved in the problem. Unfortunately it is not able to manage those kind of uncertainties and ambiguities that have not a random nature: these are the so called "*subjective uncertainties*" deriving from the judgment and experience of the technicians in charge of the *structural safety assessment* for existing buildings. The difficulties involved in such an evaluation, in fact, not only arise from the imprecision of the numerical data utilized in the analyses, but also on the involvement of "*subjective opinions*", that definitely have a "*non random"* nature, but belong to the class of the so-called "*linguistic data", "qualitative judgments"* or "*inaccurate information"*.

Every time that a "human expert opinion" is involved, as it happens for the safety assessment of existing structures (that is required, for example, after an earthquake in order to determine the damage level and the usability), a vague language is used. For example, in the emergency post-earthquake phase, technicians usually perform a large scale vulnerability/usability assessment compiling specific forms. In the case of traditional masonry buildings, they will classify first of all the masonry type, then evaluate a number of parameters such as the masonry quality, the effectiveness of the connections between walls or between walls and floors. All these operations are fulfilled on the basis of visual inspections only, and terms such as "*good*" or "*bad*" will be used, that will enter in the final vulnerability/usability assessment of the building: "*safe*" or *unsafe*".

It is clear, then, that the opinion expressed by different persons will never completely agree, and that this kind of uncertainty and vagueness will not only affect the visual screening performed by the experts, but also all the other additional data used in the assessment: existing documents, experimental testing results, calculations and analyses. For example, even if during the construction the technical manager has judged as *good* the execution of the concrete works (on the basis of parameters such as the results of laboratory tests on materials used, the workmanship quality, …), the building inspector could judge the same work either *fairly good* or *quite good* on the basis of the available documents and of the results of the inspection tests.

Linguistics expressions as: *good conditions*, *fairly good conditions, crucial conditions*, are regularly used from expert personnel both during the construction of a structure and during its service life, and it is quite evident that the boundary between these judgments is not *crisp* but *vague*. Indeed, only quite recently the complexity of the problem has been fully recognized: before that, the procedures used for the safety assessment of existing constructions classified the structure simply as *safe* or *not safe*, neglecting the fact that the problem is not a two-class one, but rather a multi-class one.

A classical, simple example is the damage assessment for a concrete beam on the basis of the observable cracking pattern (with regard to their dimension and extent). If, during the inspection, the technician does not observe any crack, the diagnosis will be: "*absence of damage"*. If he surveys a limited number of cracks, he will probably express the diagnosis: "*small damage"*. Similarly, as long as the number of observed cracks grows up, the final diagnosis will become: "*moderate damage", "severe damage"*, or *"very severe damage"*. Not only these evaluations are strictly subjective, but they present a range of overlapping: to declare that the damage level is *severe* or rather *very severe* is frequently only a question of points of view. It is just this "lack of crispness" that makes the structural safety assessment process so complex and tricky, calling for the definition of alternative, specialized methodologies for the management of "*qualitative and vague judgments"*. (Ross [4])

In this context, the fuzzy logic appears the most qualified tool for the processing of numerical data and uncertain information in order to obtain a linguistic description of structural damage.

The fuzzy logic was introduced in the 60's by Zadeh [5], who stated that the "key elements of human thought can not be represented by numbers, but rather are the *labels* of *fuzzy sets*, that is to say, linguistic values identifying *fuzzy sets*." Fuzzy sets are classes of objects characterized by a gradual transition from the *membership* condition to the *non membership* one, whereas crisp sets (that where the only one known before this new theory) only allow the drastic binary condition membership/non membership.

Hence, the theory of fuzzy sets requires the definition of a *membership function* able to associate to each element of a set the correspondent *membership degree*, that will be equal to *0* if the element does not belong at all the set and will be equal to *1* if the element belongs to the set. Between these two extremes there is a wide range of partial membership, represented by a real number included in the range *0-1*. It is just the presence of an overlapping among different sets that represents the key for handling the uncertainty and imprecision previously mentioned.

Let's now discuss the possible application of the fuzzy logic in the safety assessment of existing R.C. buildings, according to the scheme outlined in the previous paragraph. The first step of the preliminary investigation (*PHASE A*) is represented by the retrieval and inventory of all existing documents and drawings about the building, that will result in a collection of numerical data and also of qualitative and subjective judgments. The level of uncertainty related to this phase is very high: available documentation is often incomplete or even completely lacking; indirect knowledge must be derived from oral interviews; historical data will be discretionally interpreted by the technician in charge, who will translate them either in numerical score or in a concise linguistic judgment.

At this point, the fuzzy theory can be fruitfully adopted in order to transform qualitative judgments into linguistic data: this is performed by using membership functions.

In order to understand what a membership function is, let's consider a practical example. With regard to the survey of the cracking pattern on a structural element in the basic testing, typical classes of linguistic expressions will possibly be: *"small cracks", "medium cracks", "large cracks"*. These classes can be chosen as reference fuzzy sets: the membership function will be used in order to decide to which set each new acquired data does belong, and to which degree. Actually, in the basic testing phase, an instrumental, measurement of the *cracks' width* is performed, and therefore a numerical information is available. Memberships functions are specialized for "fuzzyfying" the numerical data: the surveyed crack will belong to one (ore more) of the predefined fuzzy sets: *"small cracks", "medium cracks", "large cracks",* with a certain membership degree.

The most commonly used membership function is the triangular one, that will be indeed the function adopted in the proposed algorithm. In figure 2-a the triangular membership functions used for relating the cracks' width to the fuzzy sets: "*small cracks", "medium cracks", "large cracks".*

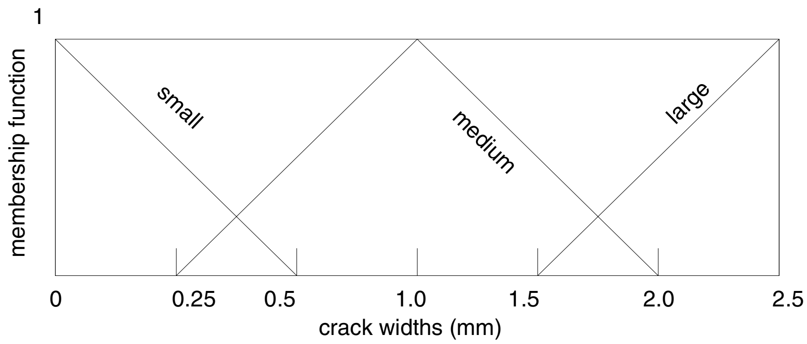

Figure 2: Triangular membership function for the input variable "cracks'width".

In the damage assessment of an existing building, several input data are required (crack dimension, residual strength of materials, amount and condition of steel, …) that will all be treated, according to the previous remarks, as fuzzy sets. There is now the need to combine these elements each with the other, in order to obtained the desired final diagnosis. This is performed by introducing proper "*fuzzy rules*", relating the above mentioned input data (resulting from direct and indirect inspections, testing, …) with the final output variable "*damage"*, that is once again an element belonging to a fuzzy set (for example: "*small damage", "moderate damage", "severe damage"* – fig. 3).

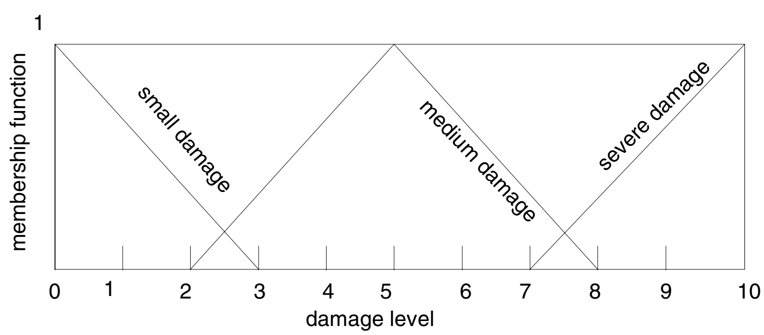

Figure 3: Triangular membership function for the output variable "damage".

An example of fuzzy rules is now reported, referred to the input variable "cracks' width":

- *if* (cracks) are **small** *then* (damage) is **small;**
- *if* (cracks) are **large** *then* (damage) is **severe.**

Of course, this is only a coarse simplification of the real procedure: actually, while assessing the health conditions of an existing building, even in the very preliminary steps more than one experimental measurement will be taken on a number of selected structural elements (columns, beams, floors). Besides the survey of the cracking pattern, a significant appraisal of thickness of bars covering will be for example performed, as well as an evaluation of the corrosion extent. This means that the management of problem is slightly more complex: in order to formulate a diagnosis, for each of the *input variables* (cracks amplitude, bars covering, …) membership functions are needed, and they have to be related to the *output variable*, expressing the *damage level.*

The fuzzy rules will accordingly be more complex, since they have to take into account the simultaneousness of different factors in the evaluation of the damage level. In the case of two 2 input variables (cracks' amplitude and bars covering thickness), an example of possible fuzzy rules will is:

- *if* (cracks) are **small** *and* (bars covering) is **sufficient** *then* (damage) is **low**
- *if* (cracks) are **large** *and* (bars covering) is **sufficient** *then* (damage) is **severe**

where for the bars' covering thickness, as well as for the cracks amplitude, the fuzzy sets: *poor rebars' covering, sufficient rebars' covering* and *good cover* have been defined. So, in general, for each specific situation it is required the definition of the following elements: *input variables*, *output variables* and the related membership functions; *if-then* rules.

In the research work carried out and presented in this paper, the diagnosis procedure is performed by applying the outlined fuzzy theory-based scheme, according to a hierarchic structure. First of all, the assessment of each individual structural element (beam, column, floor) is performed, obtaining its damage level. The analysis then widened to the whole storey, processing the data about all the structural elements belonging to it in order to evaluate the storey damage level. Finally, the overall judgment on the health of the building is obtained combining the information about all the storeys, the foundations and the ground.

A FUZZY LOGIC-BASED ALGORITHM FOR THE MANAGEMENT OF THE DAMAGE ASSESSMENT AND REHABILITATION OF EXISTING R.C. BUILDINGS

Selection of the relevant input data, methodology for their retrieval and inventory

Before describing in more detail the structure of the fuzzy based algorithm, it is worth making some remarks about the choice of the set of relevant input data on the basis of which the formulation of the judgments will be made, and about the methodology concerning their retrieval and inventory.

First of all, it is clear that a clever selection of the data to be collected about the building must be performed: not always the excess of information results in a significant improvement of the knowledge obtained, and moreover it can be uselessly time and money consuming. A wise approach would rather suggest to restrict the set of input data on the basis of the criteria of simple availability and actual high relevance. Then, a well organized and systematic protocol in this preliminary phase is crucial in order to provide an ordered and easily manageable database, and to avoid additional errors. Hence, a proper model-form for collecting the necessary information has been prepared, adopting a structure consistent and effective with respect to the implementation in the algorithm that will compute the "damage" (the word *damage*, from now on, in a very general sense, will mean a synthetic judgment derived from a number of partial factors).

The forms to be used in the different phases of the diagnostic protocol should trivially contain all the fields required as an input by the algorithm, organized in such a way to permit the correct implementation in software. Of course, then, they should be easily comprehensible by the operators in charge with the on site compilation: in some circumstances it will be necessary to require the formulation of a qualitative judgment on the basis of a prearranged linguistic scale. For example, the judgment about the workmanship quality could be expressed as: "*very poor", "poor", "fairly good", "good", "very good"*. Similarly, the cracks extension in a structural element could be classified as "*very limited", "limited", "not much extended", "enough extended", "very extended"*. In other situations, the attribution of a numerical score in a fixed scale will be preferred.

BUILDING DESCRIPTION FORM	
General Data	
Year of construction	
Structural typology	Frame Columns and shear walls Shear walls Continuum walls
Seismic zoning	I II III IV
Data about the structural elements	
Floors	mixed concrete-brick cast-in floor precast rafters lattice rafters lattice plates ribbed floor slab
	unidirectional bidirectional slab
Presence of stiffening concrete cores	only columns rigid stairwell shear walls rigid stairwell and shear walls
Beams	double order of main beams main beams and secondary beams
	only rigid beams only slender beams both rigid and slender beams
Foundations	plinths one directional beams grid of beams concrete bed piles

Figure 4: Descriptive form of the building.

Let's consider, in order to illustrate the procedure, the example of the assessment of cracks extension in a structural element. The cracking extent could be judged taking as a reference a numerical scale growing from 1 to 5 as long as the damage increases from a *small* level to a *severe* one. The form will be appropriately equipped with reference figures and instructions illustrating the most common cracking patterns, in order to guarantee a better uniformity among the evaluations of the different operators performing the surveys. With regard to the damage evaluation in concrete walls and columns, the European Code 8 [6] supplies a scale of five damage levels (fig. 5).

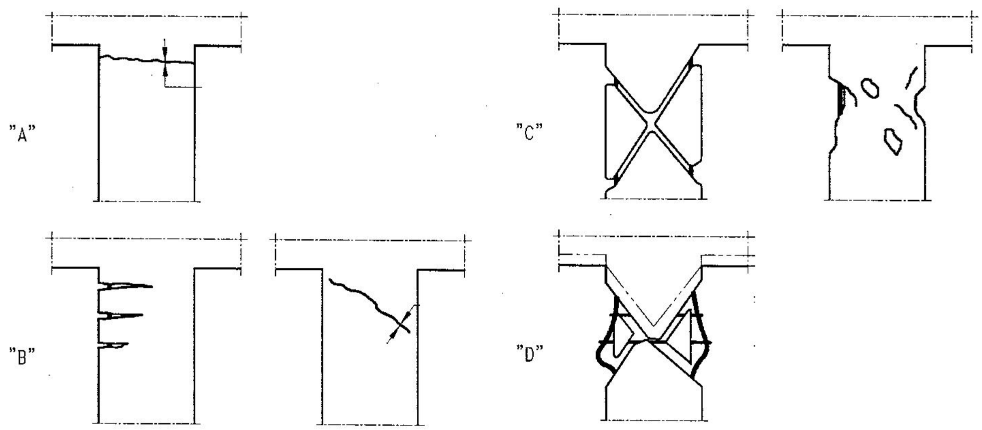

Figure 5: Damage levels from EC 8.

Following these guidelines, in the implemented algorithm a damage scale in the range 0-10 is proposed, in order to allow a finest tuning of the evaluation (fig. 6, 7).
According to the protocol outlined in the previous section, the fuzzy algorithm manages the assessment of the damage in two consecutive phases: Preliminary Investigation-*Phase A*, In-depth Investigation- *Phase B*. For each one of them, a properly chosen set of data and information is collected and processed for the formulation of a synthetic final assessment.

BASIC TESTING	**Concrete hardness:** from 5 Mpa to 55 MPa
	Reinforcing bars amount (to greater steel percentage and diffusion corresponds a higher score): from 0 to 10
	Bars covering thickness : from 0 to 3 cm

VISUAL INSPECTION (Worse is the evaluation, higher is the score)	**Cracks extension:** from 0 to 10
	Reinforcement bars deterioration: from 0 to 10
	Concrete deterioration: from 0 to 10
	Workmanship defects: from 0 to 10

Figure 6: Input data for visual inspection and basic testing (Phase A).

ELEMENT DAMAGE	Characteristic compressive strength of concrete (RCK): **from 5 to 55 MPa**
	Cracks width: **from 0 cm to 1 cm**
	Characteristic tensile strength of steel (Ftk): **from 100 MPa to 500 MPa**
	Corrosion **(worse is the evaluation, higher is the score): from 0 to 10**

Figure 7: Input data and score for the damage in structural elements (Phase B).

The Phase A is aimed at obtaining a coarse but general and wide comprehension of the conditions of the building. It is also useful in order to decide if a prompt provisional intervention is needed, if more detailed investigation are needed or simply if the situation is completely safe and requires no further analysis.
According to the recommendations given by CEB-FIP [1, 2] and EC8 [6], the analysis is organised in three consecutive steps, each of which provides an intermediate judgment that will enter in the fuzzy algorithm for the formulation of the final Phase A assessment (fig. 9):

- *Typological and structural description; existing documentation*:
  The data resulting from the general survey and from the available original design documentation (fig. 4) are examined and evaluated (drawings, structural analyses, structural details, certificates of materials, structural testing, maintenance and interventions documents, diagnostic reports, in-force technical laws, constructive techniques).
- *Visual inspection:*
  visual evaluation of cracks (extension an amplitude); concrete condition (degradation, covering thickness); reinforcing bars condition (corrosion).
- *In situ experimental testing*:
  appraisal of the concrete superficial hardness and homogeneity (rebound hammer, ultrasonic device), concrete delamination map, amount and position of reinforcing bars, corrosion of reinforcing bars, reinforcement bars covering, cracks width.

In the step 1, the synthetic description of the assessed building is performed, outlining the general characters, identifying the main cracking patterns and structural lacks both in the overall organization and in the local arrangement of the structural elements and in the constructive details. For example, it is necessary to identify the age of the building; the general structural organization and the structural type of the main substructures (vertical elements, floors, foundation, ..); the constructive techniques. Then, the some specific features of the building will be inspected and evaluated: geometric horizontal and vertical regularity; workmanship quality; destination and actual, and so on. This phase of the diagnostic procedure is very important in order to better understand the damage and degradation situations, correctly define the risk levels and properly plan the strengthening measures. These data can be usually retrieved quite easily from the technicians, by means of the form shown in figure 4.
In order to simplify the exposition, it is supposed that after the data have been collected, the technician directly formulates an overall judgment and attributes a numerical score comprised in the range *0-10* (the more severe are the observed structural lacks, the higher will be the assigned scores – figure 6). In general, the judgment on the first step could instead derive from a fuzzy analysis, as it has been actually done for the successive steps 2 and 3 (visual inspection and basic testing), for which the selected input data are represented in figure 6. These *input data* will enter in the *fuzzy toolbox*, which will extrapolate first a partial evaluation, then a combined one.
The In-depth investigation (*Phase B*) is longer and involves more detailed and expensive instrumental inspections (laboratory destructive testing, direct examination of the structural elements after the removal of plasters and claddings, loading tests, …). Consequently, the data available (both numerical and linguistic ones) will be much more consistent and precise.
Once again, in order to make the exposition simpler, the number of input data selected for the damage evaluation for each step of the Phase B has been reduced set (fig. 7).

Structure and implementation of the algorithm

In order to evaluate the deterioration of the materials, the safety level, the possible need to operate a strengthening or repair intervention, an fuzzy-logic based assessment algorithm is proposed. The "fuzzy toolbox" package of *Matlab* [7] software is exploited to this aim.
The starting point, as it has been pointed out in the previous sections, is the availability of an inventory of data and information derived from the investigation on the analyzed building, the collecting and organization of which is performed by using the survey forms described in the previous subsection.

For each of the diagnostic phases, a set of sequential operation is performed: at each step data are recorded in the program, fuzzyfied and then processed in order to obtain an intermediate output. At the end of the chain, the combination of the partial results provides the safety assessment, in the form of a qualitative judgment, together with a numerical score.

PHASE A – Preliminary investigation

The general description of the building and the available documents about the examined building are summarized in the forms shown in figure 4. They are evaluated by the operator by means of a penalty factor (the score is expressed in the scale 0-10: the more severe the structural faults, the higher the scoring). With regard to the visual inspection and the basic testing, instead, starting from the individual score assigned for each single test or observation (fig. 6), two summarizing overall outputs are generated by the application of a proper set of fuzzy rules: they are called "visual damage" and "basic tests damage", respectively.

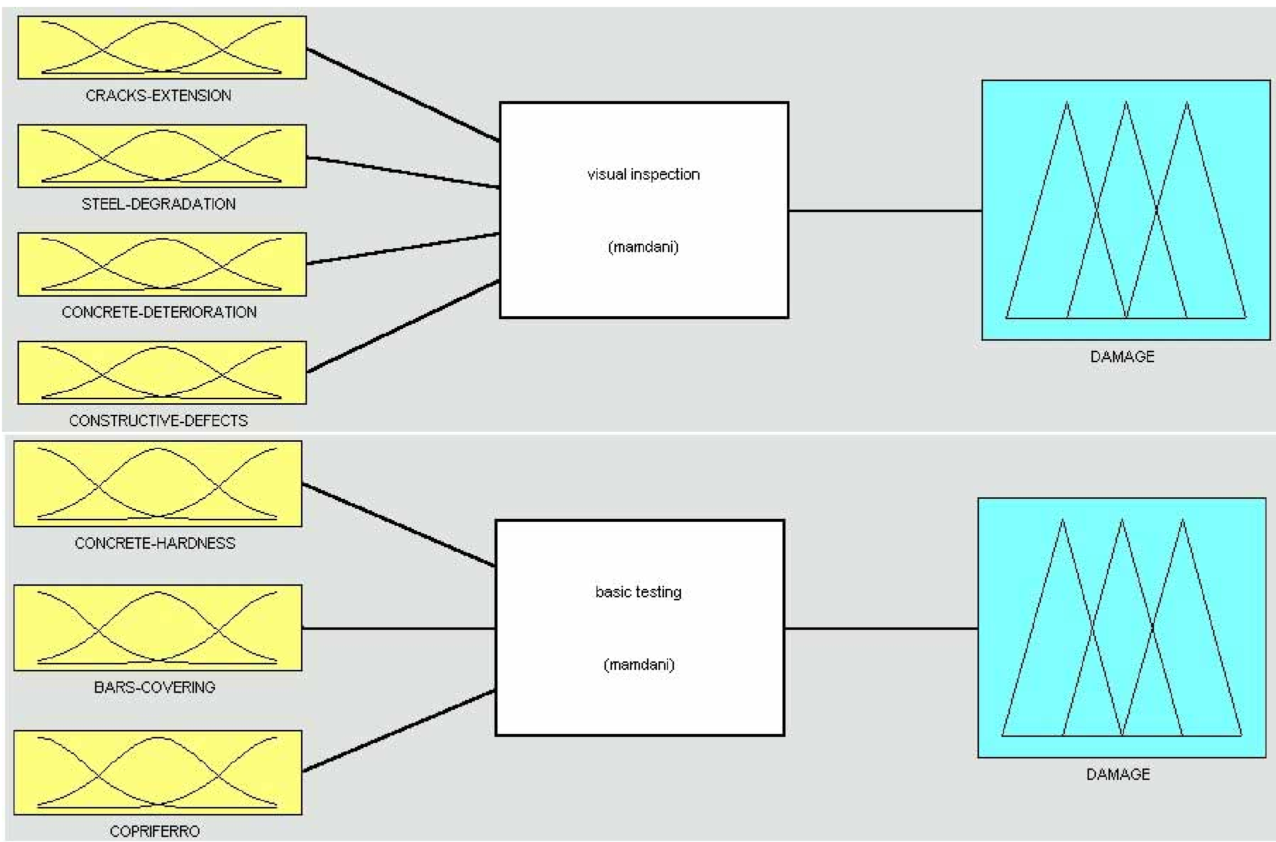

Fig. 8: The "Black box" for the visual damage and the basic testing damage.

In figure 8 the scheme of the two black boxes is shown: the input data, represented by the scores of the individual observations and testing, are processed through the fuzzy rules, providing the value of the damages. At this point the judgment of the visual inspection and basic testing damage are combined with the result derived from the evaluation of the general features of the structure (this step, as previously stated, is performed with no fuzzyfication). The diagnosis about the building, with regard to the *Phase A* is eventually obtained from these three partial scores (fig. 9), and is once again expressed with a coefficient varying in the interval *1-10*.

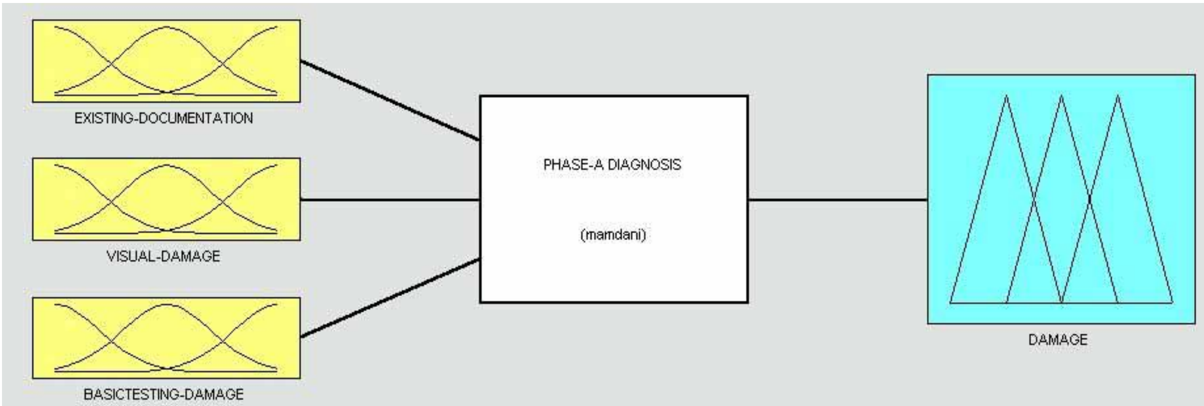

Fig. 9: The "Black box" for the Phase A final diagnosis.

PHASE B – In depth investigation.

The whole phase is managed by a nested fuzzy algorithm: starting from the assessment of the single structural elements, and progressively proceeding through the structural hierarchy (element/storey; ground/foundation/superstructure), input data are processed and collated in order to obtain the *Phase B* - assessment of the whole building. It is worth remarking that part of the results provided by the preliminary investigation (for example non destructive testing data) could be used also at this stage.

In the presented algorithm, only in order to simplify the exposition (but the general applicability of the algorithm will be not invalidated), it is supposed that we are dealing with a maximum 4-storey building. At each storey, four classes of structural elements are singled out: 1. columns; 2. main beams; 3. secondary beams; 4. floors. For each class of the examined storey, all the individual elements are surveyed, identifying a set of significant parameters: characteristic resistance of concrete and bars (Rck, ftk); corrosion level; cracks' extent (fig. 7), which will enter in the definition of the "damage level" for the considered structural element (fig. 10). For the total number of elements present at the storey, an averaged score comprised within the range *1-10* (fig. 11) is assigned, considering not only the mean damage grade but also the scattering. Once all the classes have been examined, an overall damage level for the storey is computed (fig. 12). At this point, the assessment of the superstructure, which will result in the usual scoring from *1* to *10*, is performed combining all the storeys' data.

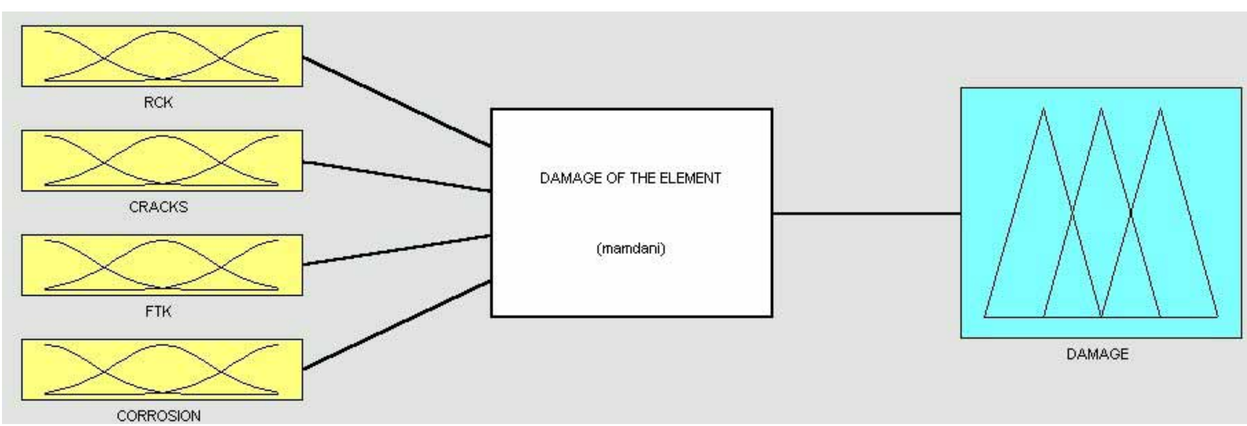

Fig. 10: Parameters used in the damage assessment for the different classes of structural elements.

STOREY DAMAGE	Column damage: **(worse is the evaluation, higher is the score): from 0 to 10**
	Main beams damage: **(worse is the evaluation, higher is the score): from 0 to 10**
	Floors damage: **(worse is the evaluation, higher is the score): from 0 to 10**
	Secondary beams damage: **(worse is the evaluation, higher is the score): from 0 to 10**

Figure 11: Input data and scores for the damage in the storey.

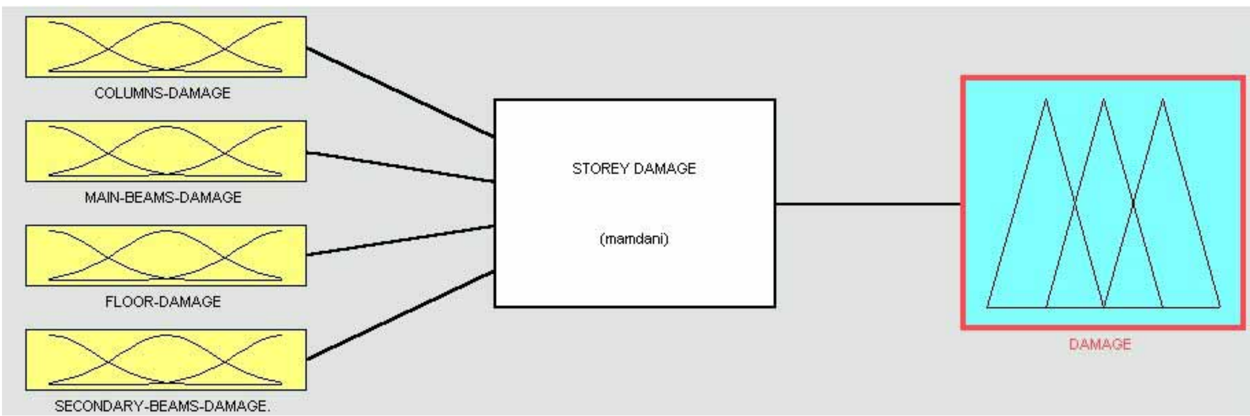

Fig. 12: Parameters used in the damage assessment for the whole storey.

The assessment of the foundation follows the same logical structure of the other structural classes. In order to complete the assessment of the building, information about the ground conditions is included: the parameters considered are: the limit stress for the soil; the Winkler coefficient; the homogeneity of the mechanical characteristics of the ground.
Finally, the Phase B final diagnosis for the building is determined from the processing of all the above defined input data (super-structure damage, foundation damage, ground damage – fig. 13) through the fuzzy black-box (fig. 14).

PHASE B FINAL DAMAGE	**Super structure damage** (the more severe the damage, the higher the score) **from 0 to 10**
	Ground Damage (the more severe the damage, the higher the score) **from 0 to 10**
	Danno fondazione (the more severe the damage, the higher the score) **from 0 to 10**

Fig. 13: Input data and scoring criteria for the PHASE B final diagnosis.

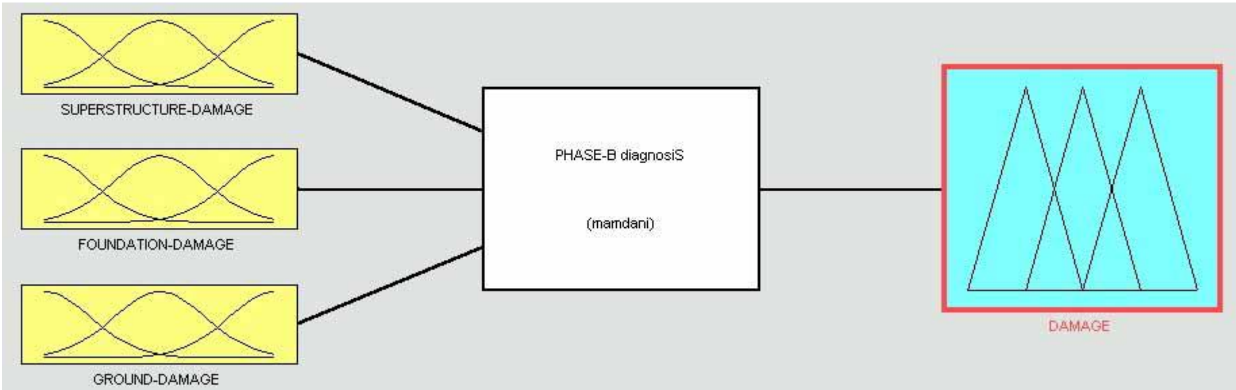

Fig. 14: "Black box" for the PHASE B final diagnosis.

REFERENCES

1. CEB-FIP. "Strategies for Testing and Assessment of Concrete Structures". May 1998. Bullettin d'Infomation No. 243.
2. CEB-FIP. "Management, maintenance and strengthening of concrete structures". April 2002. Bulletin d'Infomation No. 17.
3. IABSE Colloquium. "Remaining Structural Capacity". IABSE Report Volume 67. Copenhagen: 1993.
4. Ross T. J., Sorensen H. C., Savage S. J., Carson J.M. "DAPS: Expert system for structural damage assessment". Journal of Computing in Civil Engineering ASCE 1990, 4 (4): 327-348.
5. Zadeh L.A. "Fuzzy sets". Information and Control, 1965.
6. "Eurocode 8: Design of structures for earthquake resistance - Part 3: Strengthening and repair of buildings". Draft 4. 2003.
7. "Fuzzy Logic Toolbox: Users Guide", Users guide of MATLAB's Fuzzy Logic toolbox.