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AMADEUS: a KBS for the Assessment of Earthquake Damaged Buildings

AMADEUS: un SBC pour l'évaluation des constructions endommagées par un séisme

AMADEUS: Ein Expertensystem zur Beurteilung von erdbebengeschädigten Bauwerken

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SUMMARY
AMADEUS is a prototype of a knowledge-based system for on site assistance to non specialist engineers in the emergency condition assessment of buildings damaged by an eartquake. It provides a detailed guide to the survey and evaluation of the seismic damage to masonry constructions. A data base is integrated with the system for the automatic storage of the information collected during the inspections.

RESUME
AMADEUS est un prototype d'un système de traitement des bases de connaissance dont le but est d'assister des ingénieurs non spécialisés dans l'évaluation in situ de l'état d'endommagement des constructions ayant subi un séisme. Ce système offre un guide détaillé pour le relèvement des dommages subis par les constructions en maçonnerie suite à un tremblement de terre, ainsi que pour l'évaluation de l'état desdites constructions. Une banque de données est intégrée au système pour le stochage automatique des données relevées lors des inspections.

ZUSAMMENFASSUNG
AMADEUS ist der Prototyp eines Expertensystems zur Entscheidungs hilfe im Falle von erdbebengeschädigten Gebäuden für den dazu nicht speziell ausgebildeten Ingenieur auf der Baustelle. Das System liefert einen detaillierten Überblick über seismische Schäden von gemauerten Bauwerken und deren Auswertung. Zur automatischen Speicherung von Informationen aus bereits aufgetretenen Schadenfällen, ist dem System eine Datenbank angeschlossen.

1. INTRODUCTION

After an earthquake strikes a populated area, a large number of buildings suffer damages of various degrees of gravity, possibly leading to the total collapse of the structure. Building officials are then faced with chaotic and confusing circumstances during which they have to make quick and reliable judgments assessing the damage degree, the safety, and the usability of these buildings. This operation is referred to as *Emergency Post Earthquake Damage Assessment* (EPEDA). It consists in a quick reconnaissance of the buildings in the area hit by an earthquake to determine whether they can still assume the functions they had been designed for, without a substantial change in the safety conditions that existed before the seism.

The primary purpose of the emergency damage inspection is to save human lives and prevent injuries by identifying buildings that have been weakened by the earthquake and are therefore threatened by subsequent aftershocks. The other important objective of this operation is to avoid unnecessary waste of resources and additional human suffering by identifying habitable and easily repairable buildings, and hence reduce the number of homeless people and the economic cost of the disaster.

Unfortunately, after an earthquake, the demand on building experts often exceeds by far their availability. In many instances, non-experienced engineers and poorly, if at all trained technicians are assigned to this difficult task without specific criteria about what to do and how to decide.

1.1 Current Approaches to the Emergency Post Earthquake Damage Assessment

Despite its relevance, the emergency post earthquake damage assessment has not received from the concerned institutions and authorities the attention it deserves. In the case of new constructions, for instance, the path to be followed by the engineer is fairly clear. Codes regulate the design for given levels of safety established by official institutions. Not only are the procedures clear, but also the engineer or technician involved in the design is protected from liability as long as the design is in agreement with the corresponding texts. Unfortunately, nothing similar exists in the field of post earthquake damage assessment. The inspector is left alone and the decision as to whether the building is safe, is simply based on his or her *experience and best judgement.*

The operation of damage assessment is generally done in the following way: the building inspector has to fill out a form consisting of a series of questions covering general informations on the type of structure, its location, and the state of damage of the building. Up to date, these questionnaires have been designed as tools for uniform gathering of data. There is no intention to guide the inspector in the reasoning about the situation he or she is confronted with, nor is there an attempt to assist him or her in the evaluations and decision-making process. For instance, the assessment of the degree of damage to the structure requires from inspectors a qualitative assessment which, most often, is beyond their capabilities; consequently, unexperinced engineers usually tend to be overly conservative or, more frequently, to demonstrate their confusion by statements like "*unable to classify, reinspection recommended*". Only few investigators can, thanks to the expertise they acquired through years of experience, make judicious and reasonable judgements.

1.2 Proposed Approch to Emergency Post Earthquake Damage Assessment

Due to the importance and to the extent of the problem, official institutions in highly seismic regions, like Italy, have been recently concerned with the issue of EPEDA. One of the authors, in the context of his work within the "Gruppo Nazionale per la Difesa dai Terremoti", has developped a questionnaire accompanied by a set of instructions and guidelines on how to proceed in the assessment [7]. The guidelines suggest a number of steps to take during the inspection, and propose a way to reach the final decision. The methodology presented is the result of the experiences acquired through the various earthquake events that stroke Italy during the past many years, and of an effort to structure the process through which the assessment is reached.

This effort is tentative and exploratory, and is open to improvements as more knowledge becomes available. It is an attempt to define the criteria behind the condition assessment and to present them in a logical and useful format to the building inspector. However, this questionnaire and the accompanying set of guidelines present a rigid and unfriendly platform of work, especially given the emergency conditions that follow an earthquake and the associated time pressure. The problem then consists not only in developing a methodology that captures and structures the reasoning of recognized experts in the area, but also, and as importantly, in finding a flexible and transparent medium of transfer of the gathered and structured expertise to the unexperienced building inspector.

Traditional computer techniques have often provided engineering problems with efficient and fast solutions. The problem at hand however, is difficult and complex mostly due to the nature of the knowledge involved which still is, in part, an art, and for which traditional procedural and algorithmic computer techniques have proven to be inadequate. The field of Artificial Intelligence has developed a series of tools for dealing with such problems. The resulting computer systems can very effectively manipulate symbolic data and qualitative measures, and are also able, to a certain extent, to mimic human reasoning. Empirical and experience-based knowledge together with procedural knowledge, can efficiently be encoded in such systems, providing a useful product. These systems are known as Expert Systems or more generally as Knowledge Based Systems.

A portable, interactive, rule-based system for assisting unexperienced engineers or technicians during the emergency condition assessment would be a good answer to the problem of expertise-transfer, mentioned earlier. Such a system would encode the methodology followed by experts in the field and make it available to profanes. To demonstrate the feasability and the potentiality of such a system, we developed AMADEUS[1], a Knowledge Based System for assisting building inspectors during the emergency post earthquake damage assessment.

The next section summarizes the methodology previously presented in reference [7], and which is the basis for the development of AMADEUS. Next, the architecture and the principal features of the system, as well as its functioning, are described. Finally some concluding remarks are presented.

2. PROPOSED METHODOLOGY FOR EMERGENCY POST EARTHQUAKE DAMAGE ASSESSMENT

2.1 Objective and Scope

The presented methodology is described in detail in reference [7]. It is characterized by an attempt to better define the loads of reference, i.e., the loads for which the building is considered to be safe, and by an effort to provide a uniform assessment of the safety of the buildings. At first glance, the notion of loads of reference may seem trivial, but in fact, is not

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[1]Advisory Methodology for Assessment of Damages after Earthquake and Usability of Structures.

surroundings. Three risk concepts are associated with these elements: the geotechnical risk, the structural risk, and the complementary risk; in addition, a level of induced risk which is related to the danger induced by the building on its surroundings is defined. These risks, in turn, are evaluated through a consistent procedure. This process mainly involves qualitative data, generally obtained through *guided* visual inspections or through some official communications.

The geotechnical risk quantifies the hazards associated with, the soil conditions, the soil damage, and the type of foundations. Depending on these parameters, the geotechnical risk can be determined to be Low, Medium, Uncertain, or High. A possible high geotechnical risk will be a decisive negative decision factor in the global risk evaluation. In the cases where the damage to the soil under or around the building, or to the foundation system exists but is not excessive, the geotechnical risk will be a worsening factor for the determination of the global risk, and consequently, of the usability decision.

The structural risk evaluation is the central operation of this condition assessment procedure. It quantifies the actual or incipient hazards associated with the load carrying components, both vertical and horizontal, of the building. The structural risk can take two values: High or Low. The level of structural risk depends on the integrity of the structural system (or damage degree), on the level of the seismic test endured by the building, on the forecast of subsequent aftershocks, and on the structural consistency (or vulnerability) of the building.

The structural damage, which is usually the only criterion considered in the usability decision process can vary, in this formulation, along six discrete levels of gravity, going from "no observed damage" to "total collapse of the structure". For masonry structures, the system assists the user in assessing the level of damage of each structural component on the basis of the amount of crushing and cracking observed, of their position, and of their spread.

The level of the seismic test endured by the structure depends on, the intensity and magnitude of the earthquake, the position of the building with respect to the epicentral area, and the maximum historical shock in the area. This concept is an important factor in the determination of the structural risk level for the cases where the observed structural damage is not high enough to directly dictate the evacuation of the building.

The aftershock forecast is an important factor for the usability decision. It should be the object of seismological studies, and given officially, prior to the inspections, to the personel concerned with these investigations.

In the present evaluation procedure, the vulnerability is qualitatively based on typology; in the future it should be the object of more thorough investigations. The vulnerability becomes important when the aftershocks are expected to be comparable to the main shock.

The structural risk determination shows a clear attempt to rationalize the EPEDA, and to gain some insight in the behavior of buildings in the unusual environment created by the early post earthquake conditions. It also is a good illustration of the underlying reasoning process. For example, if the damage level is evaluated to be medium and the seismic-test undergone by the building very-strong, then there is no need to consider the vulnerability level of the structure. On the contrary, if the damage is light and if there is a high probability that the seismic crisis is not over yet (possibility of occurence of strong aftershocks), then the vulnerability of the building plays an important role in the determination of the structural risk level.

The complementary risk quantifies the hazards associated with sources other than the pre-cited ones. The complementary risk evaluation depends on the level of the non-structural risk and on the nature of the external risk. The non structural risk "measures" the danger associated with that easy to define: should one evaluate the vulnerability of the structure with respect to the strongest possible load? the most probable one? or perhaps, one should define some reliabilty indices? This evaluation should therefore not be left to the individual initiative of the building inspectors, but be the object of well-thought-of regulations.

Presently, it is a widespread idea that the damage state of the building is the only important decisional criterion for the usability. Therefore, the structures having slight or no damage subsequent to the earthquake, are declared to be habitable. The argument behind this procedure is that if the building sustained the present earthquake shock without damage, it is seen to be safe, and is consequently declared habitable. This rule implicitly assumes the loads of reference to be the just-happening earthquake, and thereby neglects possible stronger aftershocks. Moreover, basing the usability decision on the visible amount of damage exclusively, is a poor approach and an incomplete strategy. The insufficience of this rule of thumb becomes conspicuous in the doubtful cases, where observable damages of various degrees of gravity have occured due to the earthquake: a large dispersion of the usability decision has been noted in most historical cases. To overcome these limitations, the present methodology proposes to consider as reference loads -when possible- the seismic loads associated to the expected aftershocks for the area in consideration. The available information about, the strength of the earthquake, the possible sequence of aftershocks, the position of the builing inspected with respect to the epicenter, and the earthquake history of the site are used to assess whether the building is potentially exposed to severe loading during possible aftershocks.

Another important issue which is, as of yet, left to the personal judgment of the building inspector, is the definition of appropriate levels of safety. In the design of new constructions, these levels are regulated by official texts for the various types of structures, insuring uniformity and well considered safety. However, in the emergency post earthquake damage assessment, it is the inspector who, implicitely, chooses some level of safety. For example, the inspector can declare a building "to be evacuated" after having observed slight structural damages, in which case he is taking too high a level of safety; conversely, he can declare a building to be habitable after having reported a medium-to-high level of damage to the structure, in which case he can be taking excessive risks. This policy puts additional weight on the building inspector and results in a prevailing non-uniformity of the assessments. There is, therefore, a need for the creation of a template for decision making to uniformly guide the inspectors in their usability assessment. Moreover, since these guidelines will be partly based on the observed conditions of and around the building, an additional set of guidelines, insuring uniformity of the quantification of these conditions, is needed. The present methodology addresses these two questions and offers a more informative way of proceeding.

2.2 The Knowledge in AMADEUS

The methodology developed and encoded in AMADEUS is based on a notion of *global risk*, which is a qualitative measure of the safety of the building under inspection. The "value" of the global risk directly dictates the decision to be taken regarding the usability of the structure. If the global risk is HIGH, then the building is to be evacuated; if it is UNCERTAIN then reinspection is recommended; and if it is LOW or if there is no risk, then the building is declared to be safe and can be inhabited. It is also possible that the building become habitable after fullfillment of the specific provisions recommended by the inspector. Any of the outcomes may apply to the whole building or to only a part of it. This risk associated with the building is the result of a consistent reasoning involving four principal elements: the *geotechnical situation* of and around the building, the *state of the structural system*, the hazards due to the *non-structural elements* of the building, and the *danger induced on the building by its* non structural components which may be hazardous to poeple. The external risk quantifies the danger induced by elements surrounding damaged buildings which may endanger human lifes in or around the inspected building.

3. AMADEUS: A KBS FOR EMERGENCY POST EARTHQUAKE DAMAGE ASSESSMENT

AMADEUS is an advisory system for the condition assessment of buildings hit by an earthquake. Its purpose is to assist, in situ, the engineer during the emergency inspection following an earthquake by providing a rational and uniform methodology. Based on the inspector's observations, AMADEUS helps him/her make quick and accurate decisions regarding the severity of the damage and the habitability state of the building. In this process, it should be clear that AMADEUS is not to replace the inspector but guide him/her through the reasoning process to ensure that the engineer's approach to the problem is correct. The system also provides the inspector with the specialized knowledge required in particular situations and suggests a final decision with respect to the habitability status of the building under inspection. AMADEUS has been developed in PcPlus, a Lisp-based Expert System development Tool [11].

3.1 System Architecture

AMADEUS is a rule-based system. The knowledge base uses three structures to control and organize the information: Parameters, Rules and Frames. Parameters are specific facts or pieces of information that can hold one or more values. They are organized in sets and belong to frames. Rules embody the codified knowledge; their action is to modify values of parametres depending on the data gathered. They also are organized in sets belonging to frames. Frames are used to group parameters and rules related to a specific sub-problem, and are organized in a hierachical manner. Their purpose is mainly to help organize the knowledge (parametres and rules), in a convenient and efficient manner. They are helpful when the major task can be subdivided in minor ones, which was the case for AMADEUS. A conclusion that is reached by the system is called "goal". The final goal of AMADEUS is the usability decision. It can take the following values:

- Building Habitable
- Building Habitable through Provisions (specified by the system for completeness)
- Building to be Reinspected and thus Temporarily not Habitable
- Building to be Evacuated

These values may apply to part of the building or to all of it. Each frame is responsible for the evaluation of a sub-goal that counts toward the achievement of the final goal. The hierachical organization of the frames is shown in Figure 1.

The way the system goes about its task is illustrated in Figure 2. To reach the final decision, it needs to quantify the various risks defined in section 2.2. Its first sub-goal is the geotechnical risk, determined from the ground damage level and the condition of the foundation system, which is itself a subgoal of a lower frame, determined from the soil profile, soil conditions and foundation type. A high geotechnical risk leads to the evacuation of the building with no need to further considerations. In the other cases, the system evaluates the structural risk. Three sub-goals directly affect the evaluation of the structural risk: the global damage level, the seismic test level and the vulnerability of the load carrying mechanisms. If the stuctural risk is

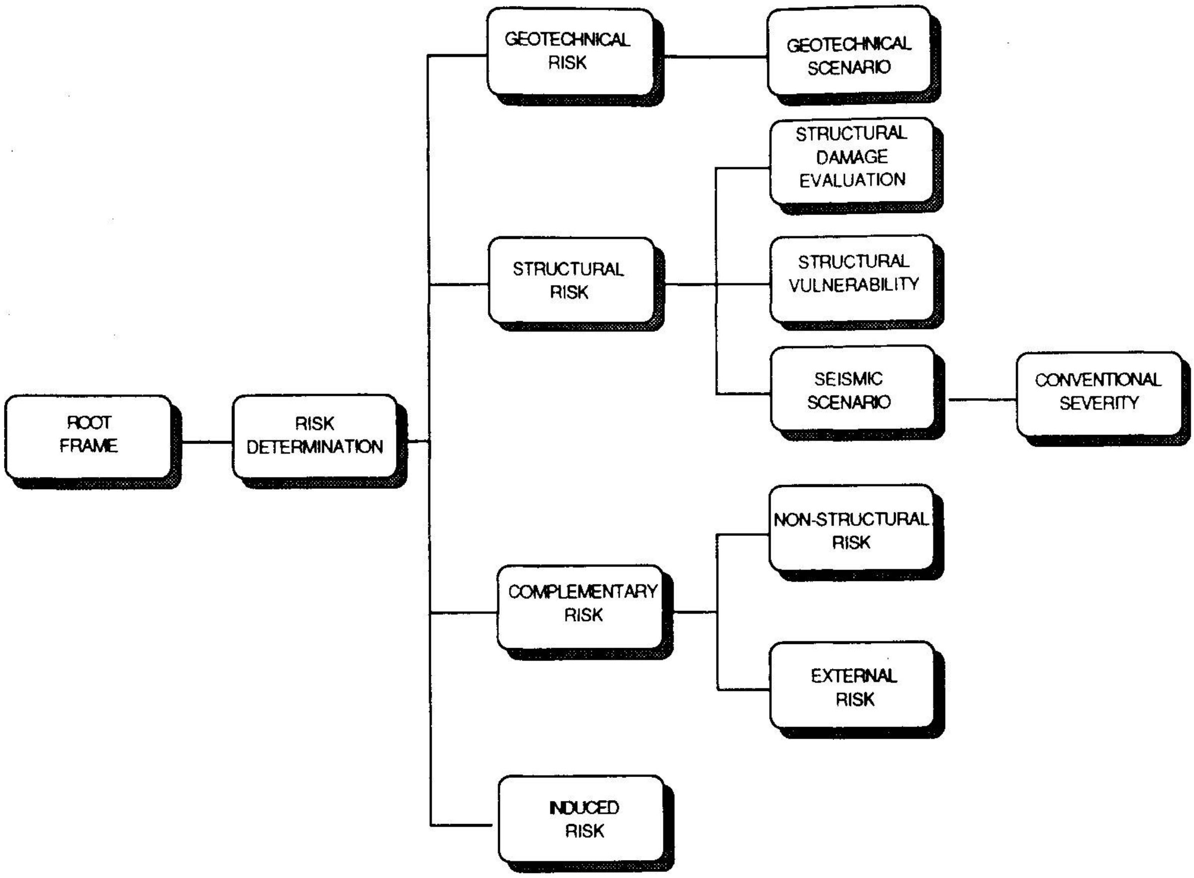

Fig.1 Hierarchichal organization of Frames

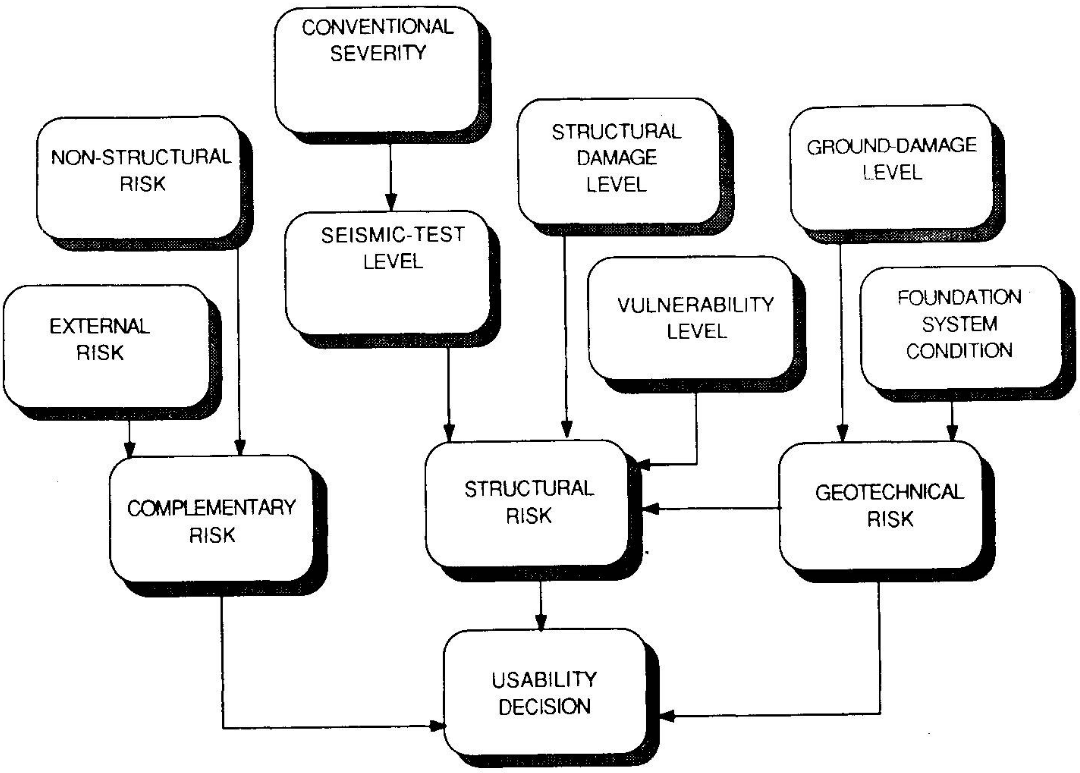

Fig.2 Dependency network

determined to be not high, the system evaluates the complementary risk. To do so, it has to evaluate two sub-goals: the non-structural risk and the external risk, the latter being determined only if the former is not decisive. After the evaluation of these sub-goals, and with the information gathered in the process, the system makes its usability decision and possible recommendations.

3.2 System Functioning and Application

AMADEUS is an interactive system and highly relies -in its decision making process- on the information provided by the user (building inspector). The system has been built so as not to ask for unnecessary information. This feature makes the interaction with the user particulartly valuable since it is more than just a sequence of data input, which is the case for the questionnaire-type form. In fact, in AMADEUS, the sequence of questions guides the inspector in reasoning about the situation. The system puts in focus the points that are worth looking at under given conditions, and ignors the details irrelevant to the particular case. Also, the use of the same methodology by all operators is important since it insures uniformity of reasoning, which is otherwise lacking in similar evaluations.

At the beginning of a consultation, AMADEUS asks the user to provide him with general information as to what the global situation is: geotechnical conditions around the building, seismic scenario, and damage levels. It also requires information about the building type and location. This step aims at helping the inspector get a global picture of the situation, as well as at providing a starting point for the reasoning process. Depending on the previous information, the user is prompted for more detailed additional information such as building type or suggested provisions. At the end of the consultation the system is to suggest whether the building is habitable, habitable through specific provisions, temporary not-habitable and requiring more accurate inspection, or to be evacuated.

At any point of the consultation, the inspector can ask the system why it requires a certain type of information, or how it arrived at a given partial conclusion. The inspector can also, at any time, change the value of one or of a number of input to investigate the impact of the observation under consideration on the final decision. This feature is valuable since it helps the engineer in assessing the reliability of his/her assessment.

The shell used for the development of Amadeus allows for inexact inferencing through the use of certainty factors. Certainty factors are uncertainty quantifyiers based on Measures of Belief and Measures of Disbelief. Amadeus allows the user to input some of the observation by using the certainty factors as quantifyiers of the inspectors confidence in his/her observations. These measures are carried along in the reasoning associating corresponding certainty factors to the conclusions reached. Thanks to these measures, it is possible to carry on simultaneously multiple reasoning. One downside of the system is that it is inflexible in the choice of the method of computation of the certainty factors of the outcome.

A database system for the storage of the information collected during the inspection has been designed and implemented on dBaseIIIPlus™. It allows for the storage of more than 200 fields per building, organized in five related files. Identification data of the building and of the inspection team, as well as a detailed inpection record is automatically transfered to the database at the end of each consultation. From AMADEUS, the user has the option of accessing the database system for querying, viewing, editing or printing previoulsy stored records. The emergency management authorities will, therefore, benefit from a more direct, complete, and efficient access to the results of the inspections.

AMADEUS methodology has been recently applied to the usability assessment of the masonry constructions in BARREA, a small historical village in central Italy which has been evacuated and clesed for more than two years after the earthquake of May, 1984. Detailed results of the survey are presented in [5], where it is shown how the influence of the evolution of the seismic scenario is reflected in appreciable changes in the usability of the buildings.

4. CONCLUSION

AMADEUS is still in the prototype stage, but the knowledge-based approach chosen for its implementation will facilitate its incremental development and refinment as more knowledge becomes available. The database integrated with the system will help the emergency management authorities in expediting the processing of the inspection data and the selection of the appropriate intervention. Once again, it is important to stress that the system assists the inspector in focusing the attention on the relevant issues during the inspection, and suggests some conclusion about the building usability; its objective is not that of replacing the inspector's decision making for which he or she remains fully responsible.

In conclusion, AMADEUS, providing a detailed guide to the survey and evaluation of the seismic damage of buildings, promises to contribute to the improvement of the quality, uniformity, and efficiency in the usability assessment process, and - more in general - suggests that knowledge-based systems can be effectively used in the surveying and diagnostic tasks often encountered in civil engineering.

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