SESSION 2

Expert Systems for Operation, Maintenance and Damage Assessment of Structures

Application de systèmes experts dans l'exploitation, la maintenance des structures et l'évaluation des dommages

Expertensysteme in Betrieb, Unterhaltung und Schadenermittlung von Bauwerken

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Knowledge-base Systems for Structures in Service

Systèmes de traitement des bases de connaissance pour structures existantes

Systeme für Wissensgrundlagen in Verbindung mit bestehenden Konstruktionen

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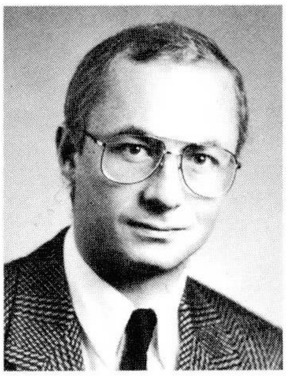

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SUMMARY
Engineering activities related to structures in service are particularly suited to applications of knowledge-processing technology since the number of problems is increasing while appropriate knowledge remains poorly distributed. This paper examines the potential for such applications and presents a small system in order to demonstrate the advantages of rapid development of prototypes. Also, advances in artificial intelligence and improvements in hardware create a situation where hybrid reasoning techniques are feasible for many problems associated with existing structures.

RESUME
Les techniques de traitement de la connaissance s'appliquent particulièrement bien au domaine des structures existantes, car l'augmentation du nombre de problèmes n'est actuellement pas suivie d'une amélioration correspondante de la transmission des connaissances. Cet article traite les possibilités d'application de telles techniques et présente un petit systéme pour démontrer les avantages de développer rapidement des prototypes. De plus, on suggère que les progrès réalisés en intelligence artificielle et les améliorations du matériel informatique rendent possible l'application des techniques de raisonnement hybride à la résolution des problèmes liés aux structures existantes.

ZUSAMMENFASSUNG
Probleme in Verbindung mit bestehenden Konstruktionen eignen sich speziell für die Anwendung von Techniken der Wissensverarbeitung, besonders weil das entsprechende Wissen wenig bekannt ist. Der vorliegende Artikel behandelt mögliche Anwendungen und stellt ein kleines System vor, um die Vorteile einer raschen Entwicklung von Prototypen zu zeigen. Fortschritte auf dem Gebiet der künstlichen Intelligenz und der Hardware lassen hybride Beurteilungstechniken für Probleme in Verbindung mit bestehenden Konstruktionen einsetzbar werden.

1. INTRODUCTION

The number of structures exceeding their so-called design lives is increasing exponentially each year. This trend corresponds to a construction boom which began over one hundred years ago Frequently, design lives for these structures were not defined scientifically and even today, economic and political factors dominate such considerations for new structures. Historically, most design constraints have been conservative due to a lack of knowledge of material behaviour and difficulties associated with quality assurance. Therefore, most of these structures are able to remain in service well beyond their designated life.

As a result, engineers are devoting a greater proportion of their time towards tasks involving evaluation, monitoring, maintenance and modification of structures in service. Identification of the best ways to perform these tasks usually requires scientific knowledge in diverse domains, such as corrosion and fatigue, and much practical experience; traditional engineering education and standard design-office methods are rarely sufficient. Consequently, the incidence of problems related to structures in service is growing while the number of engineers skilled in identifying good solutions is limited. Therefore, such tasks are particularly suited to applications of artificial intelligence research or more specifically, development and manipulation of knowledge bases.

In spite of this opportunity, few applications of knowledge-processing technology have been implemented for structures in service. Civil engineering is a fragmented and necessarily conservative field where technological developments are not embraced blindly. Applications are hindered by factors such as uncertainty related to important parameters and difficult economic, political and social considerations.

For over ten years, other fields have experimented with technology which would be appropriate for structures in service. For example, an operational system for diagnosis in the car manufacturing industry is capable of saving tens of millions of dollars annually [1]. Specialized methods and heuristics can now be distributed widely and practical applications of machine-learning methods are becoming feasible. Also, recent developments in artificial intelligence have provided tools which may be useful to problems encountered by structures in service.

This paper identifies areas where knowledge-base systems could be applied to structures in service and reviews those systems which have already been developed. Problems typically associated with structures in service are discussed. A prototype system called CRACK CONTROL is presented. Finally, the application of more complex systems for large problems is examined considering the requirements of structures in service and recent developments of methods in artificial intelligence.

2. MANAGEMENT OF STRUCTURES IN SERVICE

Activities associated with the management of structures in service are shown in Figure 1. Over their lifetimes, structures are subjected to monitoring, evaluation, maintenance and perhaps, modification. All of these activities could benefit from efforts to organize relevant knowledge.

Monitoring in the form of regular inspections is probably the most common activity. Inspection personnel need to know what to look for, where to inspect, how to examine and how to report their findings. Knowledge-base systems can assist in such decision making, e.g. [2]. Some findings may justify an increased inspection effort. The accuracy of inspection techniques should be compatible with the sophistication of methods used to evaluate findings. Structures may also be controlled using gauges and sensors for purposes such as damping and energy conservation. Such control is relatively new and therefore, software systems which enhance performance are scarce. The number of applications will grow with increasing long-term reliability of monitoring equipment.

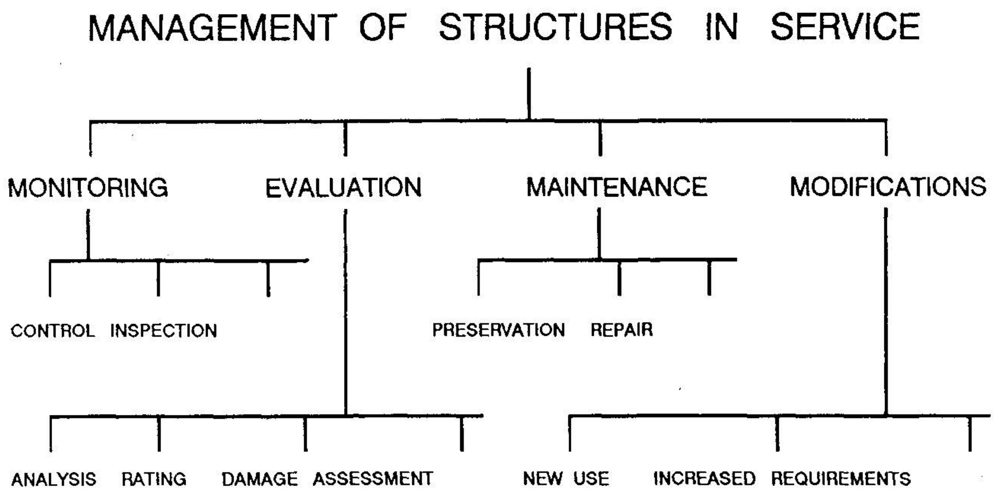

FIGURE 1 *Activities associated with the management of structures in service*

Evaluation of existing structures is the activity where the greatest effort in knowledge processing has been concentrated [3][4][5]. This concentration is understandable since often, a successful management strategy can be traced to a high quality evaluation. Applications include failure analysis, risk analysis, bridge rating and damage assessment. Analysis of structures for risk and damage due to earthquakes is thus far, the most studied domain. Other criteria for evaluating structures, such as resistance to corrosion and fire protection, have not received equal attention.

Maintaining existing structures can be extremely costly and therefore, decisions should be taken only after a rational examination of important factors. Structures need to be preserved in order to retard decay; typical activities are cleaning, painting, maintenance of drainage systems, and clearing of expansion joints. Also, structures require repair after damage has occurred. Prior to repair it is important to identify the causes of damage and evaluate whether repair is required immediately. Whereas the search for causes is common practice in many fields, existing structures are often repaired according to the characteristics of the symptom alone. Clearly, accurate knowledge of cause contributes to a successful repair.

Modifications to existing structures should be carried out in such a way that structural integrity is not decreased. Although this criterion appears obvious, there are many cases where structures have been inadvertently weakened by modifications carried out during the life of the structure. For example since 1940, hundreds, perhaps thousands, of riveted bridges have been weakened by modifications employing welding. Ironically, some of these modifications were carried out in order to reinforce the structure. A great deal of specialized knowledge is required to modify existing structures. In Figure 1, two motivations, a new use for the structure and a need to increase capacity, are provided as examples of reasons to modify structures.

Each activity in Figure 1 requires diagnostic or classification procedures to be most effective. These procedures are important for identifying good solutions and areas where more information would be most helpful. Nevertheless, a distinct focus is required for each activity since the user wishes to proceed differently for each case. Therefore, each activity has a unique set of rules which make up and control the methods employed during solution formulation. However, much of the information used by these methods is similar. Also, solutions implemented during different activities can affect each other. Common information requirements and possible interaction can be well accommodated by an integrated system. A proposal for such a system is presented in Section 4.

Many opportunities for creating knowledge-processing systems exist, and work in progress represents a small proportion of possible systems. For any effort, in system creation, a prerequisite for good solutions is a complete definition of the problem. Often, the original definition is inaccurate because domain knowledge as well as the needs of the user have not been represented appropriately. Therefore, an attempt should be made to develop a small prototype as soon as possible in order to begin testing the system at an early stage. An example of such a system is presented next.

3. DEVELOPMENT OF A SMALL SYSTEM

A system called CRACK CONTROL was developed to help engineers decide what to do if a crack is discovered in a steel structure. Intuitive repair solutions such as filling the crack with weld metal do not have the desired effects. Good decisions require a combination of scientific knowledge and experience gained through examining cracks in structures. Generally, if a crack is found in a steel structure, more careful inspection will reveal additional cracks in similar elements. If no action is taken to eliminate the cause of cracking, more cracks usually appear at other locations. These heuristics have an influence upon the knowledge structure described below.

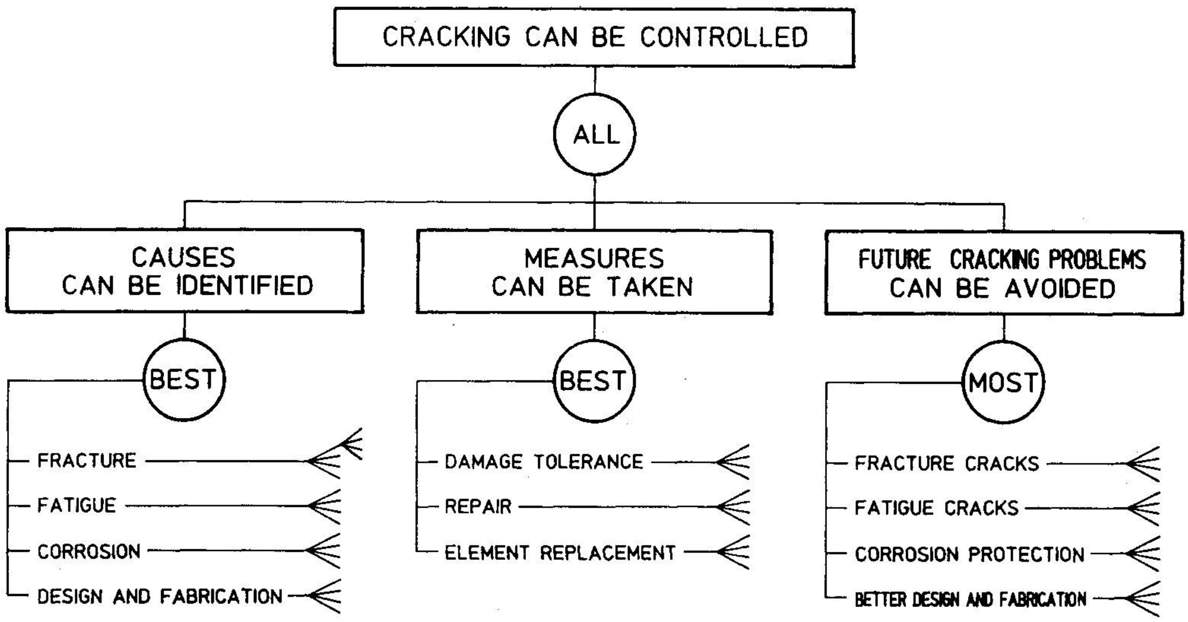

FIGURE 2 *Partial inference net of* CRACK CONTROL

The knowledge necessary to solve this problem is split into three parts, as shown in Figure 2. The first part concentrates on parameters which cause cracks in steel structures and thus, it contains the majority of the diagnostic knowledge in the system. This knowledge is split into categories which reflect the origins of cracking. Cracking may be due to fracture, fatigue, corrosion or design and fabrication practices, or most often, a combination of these factors.

The second part of the knowledge focuses on the most appropriate action, given a cracked element. Measures to be taken are subdivided into damage tolerance, repair and element replacement. Damage tolerance involves no immediate repair but an increased inspection effort. This solution is only explored under certain conditions since it is not appropriate if, for example, further crack growth could cause catastrophic collapse. Repair measures are dependent upon the causes determined in the first part. Element replacement is a valid measure when damage tolerance and repair are not practicable.

The third part of the knowledge concentrates on identifying a maintenance strategy for the rest of the structure. Once cracking has been discovered in a steel structure, the maintenance effort needs to be modified since more cracking is likely. While these considerations do not depend greatly upon the measures chosen for the cracked element, they are closely linked to the causes determined in the first part. Also, several general precautions are needed regardless of the cause of cracking.

This knowledge was implemented rapidly into a small system using a development tool specifically designed for diagnostic applications - THE DECIDING FACTOR (TDF) [6]. This tool was developed using experience gained during the PROSPECTOR project [7] and it has already been employed for diagnostic applications in civil engineering, e.g. [8].

Rather than require direct input of production rules, TDF processes knowledge organized in inference nets, see, for example, Figure 2. The user expresses opinions related to ideas low down on the net. These opinions are transferred into a belief value and multiplied by a factor to contribute to the hypothesis represented as the parent of a set of ideas. In turn, sub-hypotheses contribute similarly to hypotheses further up on the net. Belief values are combined using special logical relationships provided by TDF. In Figure 2, ALL, BEST and MOST are three of eight possible relationships. ALL and MOST pass weighted averages of belief values, whereas BEST passes the highest belief value. Thus, BEST is analogous to OR logic. The system, CRACK CONTROL, employs six relationships in all.

One of the strong points of TDF is the user interface, see Figure 3. Typically, a question screen is composed of an introductory explanation, a question, an answer box and a scale of possible answers. The user manipulates the cursor in order to adjust his answer. He need not reply definitely yes or no. Intermediate answers such as MAYBE SO and THINK NOT are possible. The middle of the scale is the reply, DON'T KNOW. This feature is very useful for applications to structures in service since information is rarely complete and never certain. This interface has been well accepted by users during tests.

Questioning proceeds from left to right in the inference net (Figure 2). It is possible to fix a range of answers, thereby allowing continued investigation of the ideas which contribute to the current hypothesis. If the user replies outside this range, questioning relating to the current hypothesis is terminated, and the system goes on to the next part of the net. For example if damage tolerance was the current hypothesis and the user had any doubt whether further cracking would lead to catastrophic failure, the system would not pursue this possibility further. Therefore, questions relating to the safety and economy of a damage tolerance philosophy would not be asked, and repair would be investigated.

A final step in the system involves a review of the recommendations provided for the particular case. Note that heuristic information is used only to identify the most appropriate recommendations. Once these are identified, the user is asked to what extent he believes that the recommendations can be carried out.

This belief determines which recommendations are reviewed and ultimately used by the system to evaluate the hypothesis that cracking can be controlled.

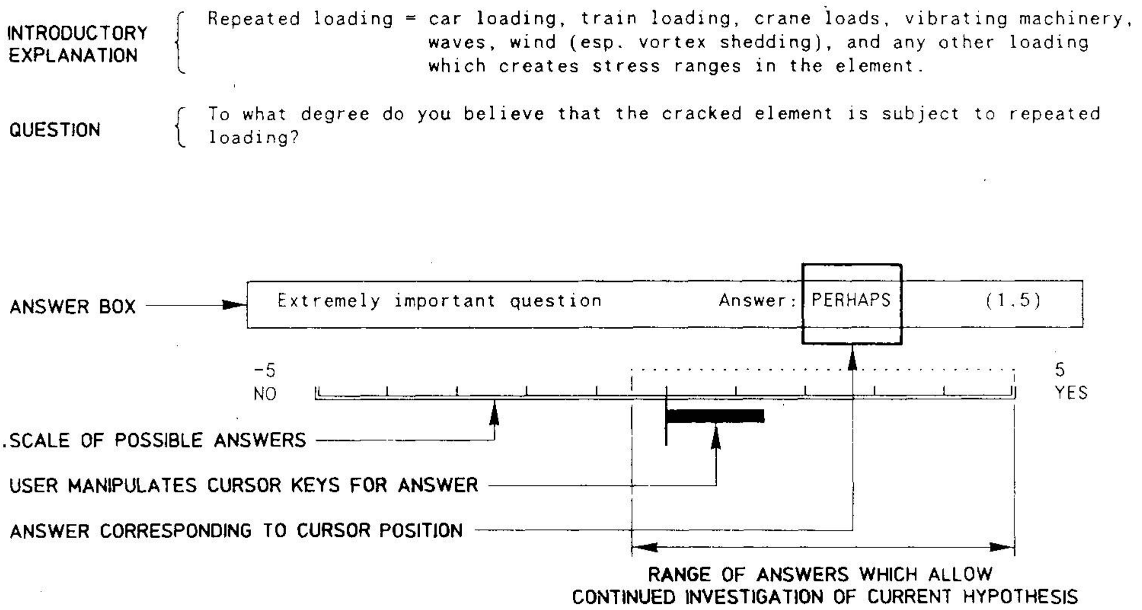

FIGURE 3 CRACK CONTROL *User interface*

Due to the ease of development, a working prototype was ready for testing two weeks after development began. Many changes were introduced after initial tests. Indeed, it was discovered that the problem was not completely defined from the start. Some measures for dealing with cracked structures were overlooked. Users employ a different language than experts and sometimes prefer that questions are raised in a different order. A small system developed rapidly using a simple tool created a situation where these differences were identified as quickly as possible.

4. HYBRID SYSTEMS FOR LARGE APPLICATIONS

Small systems developed rapidly for testing help to ensure that effort is not wasted solving the wrong problem. Knowledge is verified at an early stage and the requirements of the user become well defined. However, as the size of the problem grows, the number of assertions increases rapidly. Interaction between these assertions becomes difficult to manage and verification of all possible solutions is increasingly arduous. Well organized knowledge becomes essential.

Models and so called deep reasoning provide effective ways to organize knowledge. Generally, two types of models could be used to simulate structures in service. The first type is a mathematical description of the behaviour of the structure. Examples of models of this type include structural-analysis algorithms, fracture-mechanics simulations and fatigue-damage-accumulation techniques.

The second type is a representation where the design and function of the structure is described. Figure 4 gives an outline of such a model of a structure. In this figure, actions, such as gravity loads and wind, act on the structure. The structure is described in terms of the material employed, elements and their connections to each other, details at connections and attachments, built-in stresses, etc. The structure acts on the foundations, which for the purposes of this outline, include surrounding soil and geological properties. External factors, such as salt-water exposure, atmospheric pollution and changing ground-water levels also act on the structure and foundations. Also, changes in the behaviour of the foundations over time may in turn affect the behaviour of the structure.

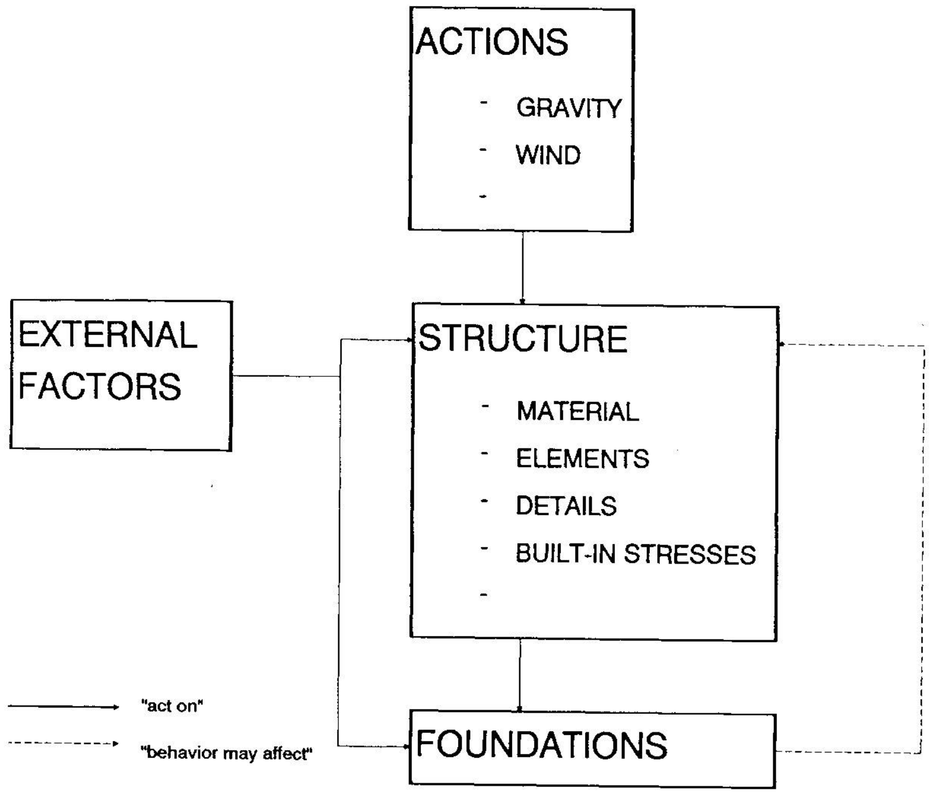

FIGURE 4 *An outline of a functional model of a structure*

Recent work in artificial intelligence has examined the advantages of deep reasoning for diagnostic activities, e.g. [9]. Using models such as the one outlined in Figure 4, domain-independent theories provide methods for diagnosis from first principles. Given a state which is observed to be outside the limits of expected behaviour, models can rapidly identify the origin of faults. They provide a means of representing knowledge for large quantities of information and complicated relationships. Therefore, models are important to the future of large diagnostic systems [10].

A further advantage of models is that they are useful for a range of activities. For example, the model in Figure 4 could assist reasoning during many of the activities shown in Figure 1. On the other hand, shallow systems using heuristic pattern matching are typically constructed to do a specific task.

However, first-principle models [9] are not useful for many types of practical problems. An exact model of the system is required, and uncertain information cannot be treated. As the number of possible faults increases, computational overhead rises exponentially. If multiple faults are considered, models are especially sensitive to problem size. Therefore, first-principle diagnostic models are most useful for medium sized closed-world problems such as small electrical circuits.

Problems associated with structures in service are very different from small electrical circuits. Important information may have a high degree of uncertainty. Relationships between objects may be poorly defined. A structure may have thousands of elements and details, and tens of load cases. In addition, critical measurements may be very difficult to carry out and external factors may include social and political considerations. These factors mean that structures in service have open-world characteristics.

Research into artificial intelligence has developed new techniques which are very useful for representing activities associated with structures in service. For example, specialized strategies used with inexact models may help reduce the effects of the open-world characteristics of existing structures. Rather than attempting to construct complete models, inexact models contain only knowledge relevant to a group of activities [11]. Other developments in non-monotonic reasoning and machine learning have created many opportunities for applications involving ill-defined problems such as those typical of structures in service. These techniques are often implemented within a system which employs shallow and deep reasoning methods.

Until recently, such hybrid systems could only be run on powerful mainframe and stand-alone machines specially developed for symbolic computation. This hardware is not compatible to the needs of civil engineering, and in particular, activities associated with structures in service. Hardware should be portable so that consultation can occur on site. Software should not be dedicated to one machine since several consultations may be needed at different places simultaneously. In the past few years these difficulties have been overcome, thereby creating the conditions necessary for practical applications of large hybrid applications in civil engineering. A summary of the considerations leading to a hybrid approach for large systems in civil engineering is given in Figure 5.

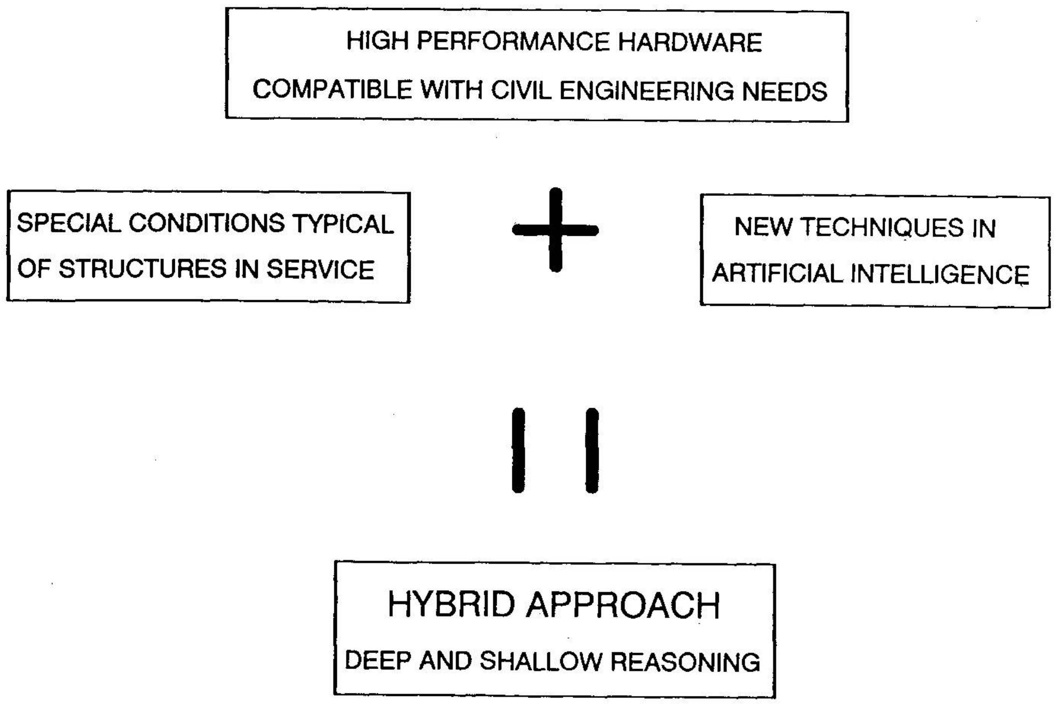

FIGURE 5 *Considerations leading to a hybrid approach for structures in service*

A hybrid approach for activities associated with structures in service is proposed, see Figure 6. The user would start the system by providing information which identifies modules that are appropriate to the problem. The majority of these modules would be activity-dependent. However, some modules, such as those used to estimate behaviour, would be used for several activities. For example, modules such as CRACK CONTROL would be chosen from a library of available small systems. At this point, the system would carry out shallowing rèasoning using heuristic knowledge which is independent of the structure in question.

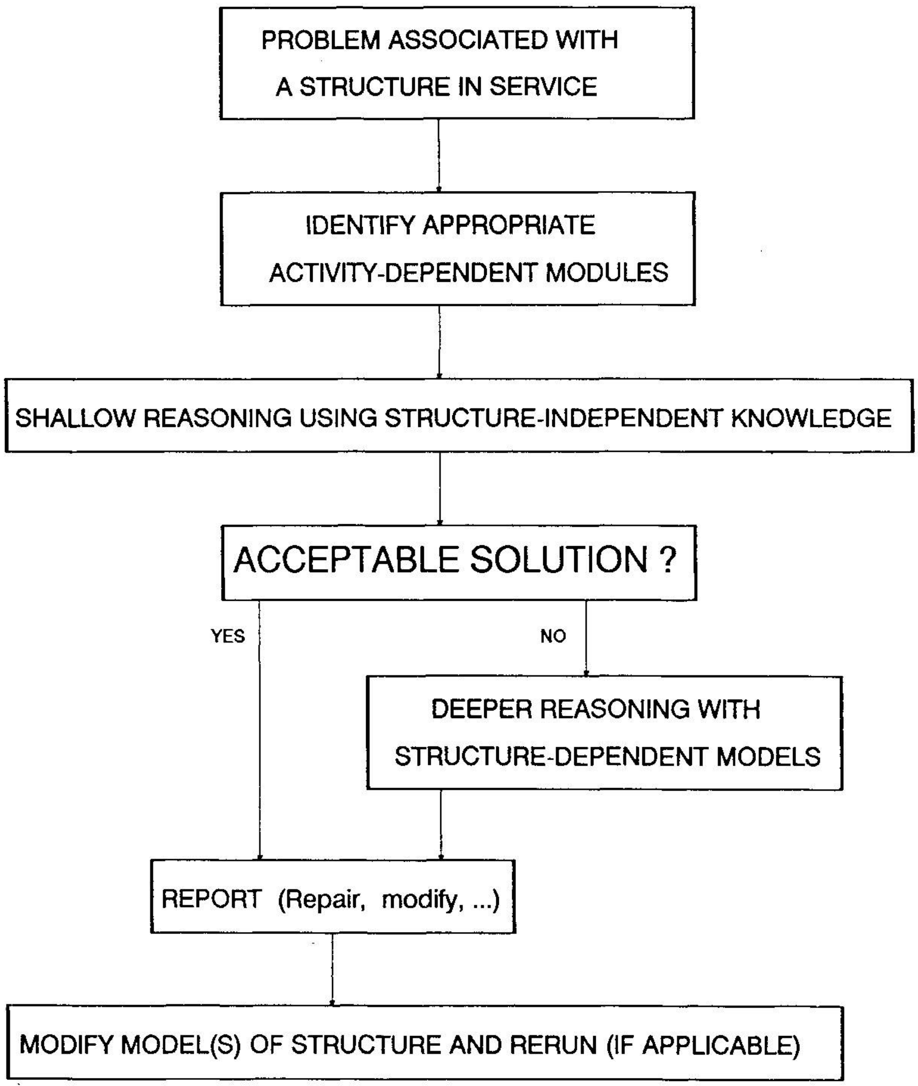

FIGURE 6 *A hybrid-system approach for activities associated with structures in service*

The findings of the system would then be assessed by the user. If an acceptable solution was identified, the system would not invoke methods of deeper reasoning. This step is comparable to traditional engineering methods since engineers typically employ more sophisticated methods when acceptable solutions are unavailable through simpler approaches. Also, if models of the structure do not exist, this step provides an opportunity for evaluating the advantages of creating them. The complexity of some structures in service could require a substantial investment in order to produce useful models.

If an acceptable solution is not identified, the system would employ deeper reasoning using structure-dependent models and more abstract heuristics. For example, if a crack is discovered in a steel structure, reasoning could help identify candidate causes of the cracking by backtracking and examining all factors which affect the element. Optimal locations for additional measurements could be identified and when new information is received, the candidate list would be updated. Most likely causes, learned from previous experience with this structure and others like it, could be placed in default slots; reasoning with such information would proceed until evidence disqualified the assumption. Similar procedures could be employed for identifying other areas at risk in the structure and for evaluation of repairs. As stated already, new research in artificial intelligence has created conditions where these capabilities are applicable to activities associated with structures in service.

The models used would be independent of activities such as those in Figure 1. In this way, information would be shared as required by the particular task. However, many heuristics would be activity dependent, especially those which control how the model is examined. Also, information obtained in the shallow-reasoning stage would be used for pruning search.

The next step is a reporting stage where findings such as recommendations for repair and inspection priorities could be presented. A final step is necessary if any repairs or modifications are carried out. In such cases, relevant models should be revised and the system rerun in order to confirm the success of the changes. In addition, this last step ensures that the models are kept up to date.

Some aspects of this approach are comparable to a multi-level approach developed for fatigue and fracture in bridges [12]. Although this study concentrated on coupling numerical and symbolic computing, many of the advantages of hybrid approaches for different reasoning techniques are demonstrated. Indeed, this study and the approach proposed in this paper suggest that structures in service can be managed more effectively with the help of modern hybrid systems.

CONCLUSIONS

1. There are many possibilities for applications of knowledge-processing technology to activities associated with structures in service. New and current work should improve capabilities to manage structures, thereby reducing costly repairs and unnecessary replacement.

2. Since structures in service experience problems which are almost impossible to define correctly from the start, it is essential that knowledge-base development begins with a rapidly developed prototype for testing with the expert and the user.

3. Models help organize the knowledge necessary for large diagnostic systems. However, for open-world problems encountered by structures in service, a purely model-based system, controlled by domain-independent heuristics, is not appropriate.

4. A hybrid system which combines shallow reasoning with model-based deep reasoning is a feasible and effective approach for structures in service.

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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

[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

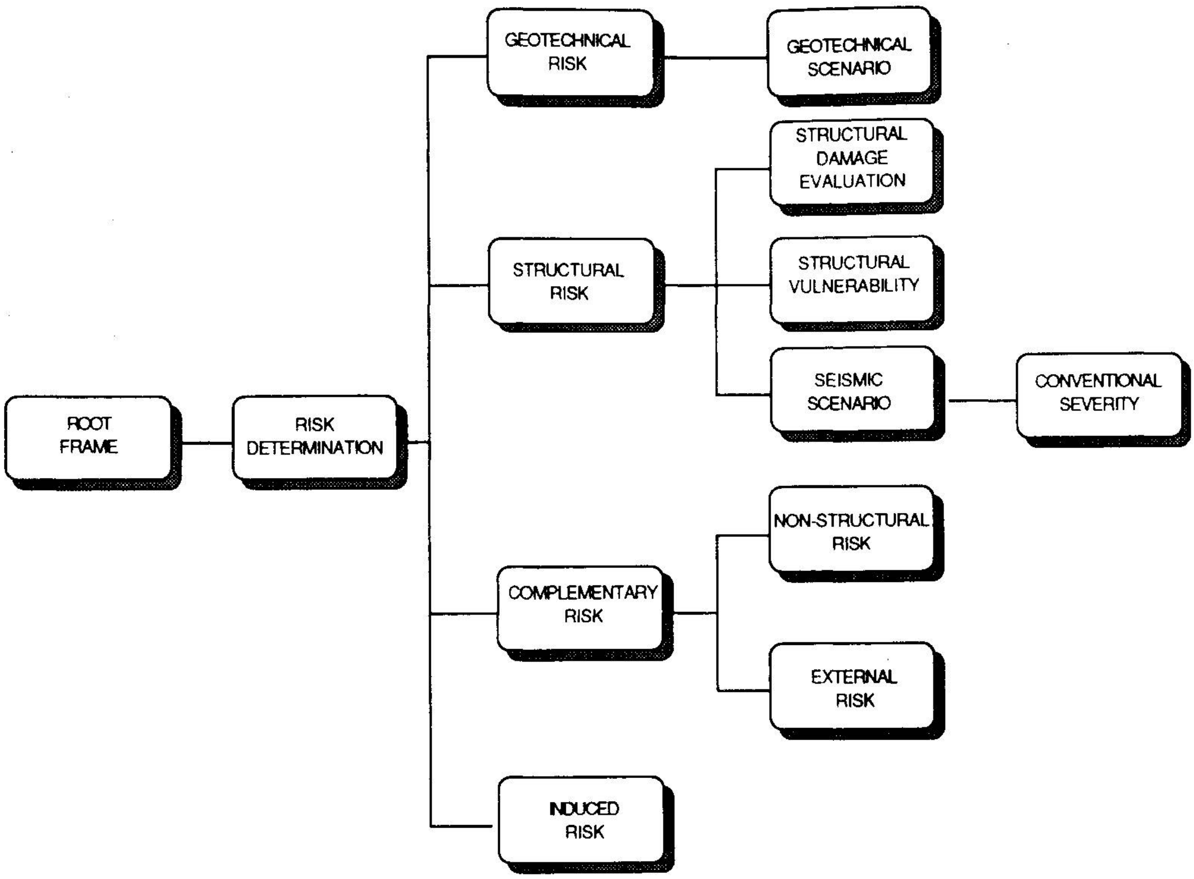

Fig.1 Hierarchichal organization of Frames

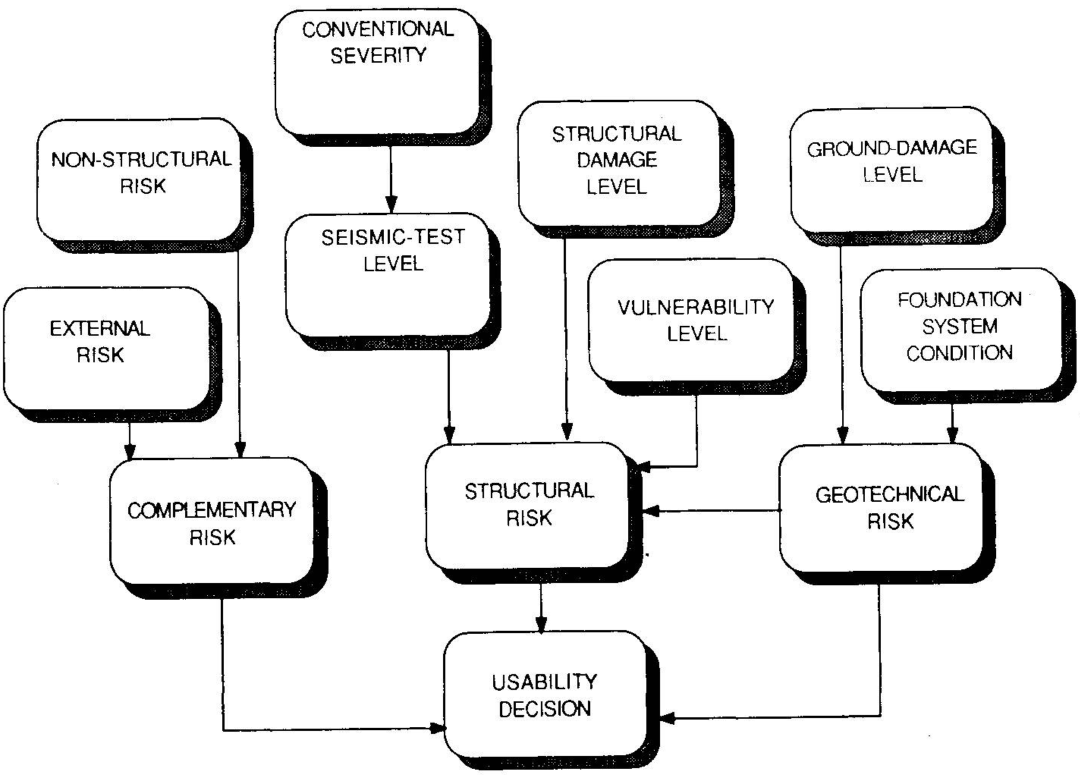

Fig.2 Dependency network

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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Expert System for the Diagnosis and Rehabilitation of Building Structures

Système expert pour l'évaluation et la réhabilitation des bâtiments

Expertensystem zur Diagnose und Therapie von Bauwerken

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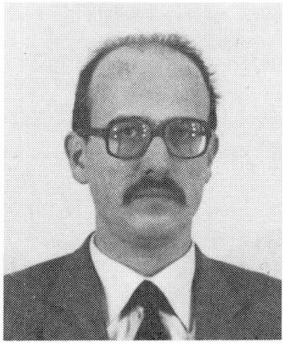

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SUMMARY

A knowledge based system, whose objectives are to support the procedures which lead to the seismic risk evaluation of buildings and to suggest possible retrofitting, is presented. The system architecture and its principal functions are described, with emphasis on the main part of the system: a model («artificial world») which describes the structure and possible behaviour of the building and its environment, at different definition levels, with qualitative and/or quantitative attributes.

RESUME

Cet article présente un système de traitement des bases de connaissances permettant l'évaluation du risque sismique pour les bâtiments et suggérant des mesures. L'architecture du système et ses principales fonctions sont décrits, plus particulièrement, la partie principale du système: un modèle («artificial world») décrivent la structure et le comportement possible des bâtiments et de leur environnement à différents niveaux de définition, avec attributs qualitatifs et/ou quantitatifs.

ZUSAMMENFASSUNG

Der Artikel stellt ein wissensbasiertes System vor, das für die Ermittlung des Erbebenrisikos von Gebäuden verwendet wird. Vorschläge für bauliche Verstärkungen werden beschrieben. Der Aufbau des Systems und die Hauptfunktionen werden erläutert, wobei das Hauptgewicht auf jenes Modell gelegt wird, das einer «künstlichen Welt» gleich, das Gebäude, sein Verhalten und seine Umwelt auf verschiedenen definierten Ebenen qualitativ und/oder quantitativ beschreibt.

1. Foreword

In the last few years the importance of retrofitting existing buildings in order to obtain a uniform level of safety in case of seismic events has been widely recognized as a major problem.
The procedures required to establish a diagnosis and to suggest a therapy either for a single building or for classes of buildings, characterized on geographical bases or on the base of common attributes, are complex and heterogeneous, requiring either theoretical knowledge and practical experience. A building can be examined on the base of direct observations, in situ or laboratory tests and numerical analysis, and subsequently retrofitted; but a rational way of operating would require a step by step economical evaluation of the risk related to a vulnerable situation, of the improvements obtainable by different possible interventions, of a deeper knowledge obtainable by new tests and analyses.

2.Objectives

Objective of the research described in this paper is the design and implementation of a system which uses artificial intelligence techniques to face the complexity of the problem.
Some features of such system have to be:

- to support the evaluation of seismic risk and to suggest possible retrofitting interventions, either for single buildings and for classes of buildings;
- to support data acquisition (planning surveys, measurements and tests), and management (storaging of information, generalization of knowledge from a specific building to groups of buildings);
- to exert control over the use of a "movable laboratory" endowed with experimental and numerical facilities.

It is well understood that the treatment of uncertainties related to knowledge and procedures plays a fundamental rôle in such a system; nevertheless in what follows this topic will not be properly addressed, since it can be treated separately from the development of the main body of the system.
In a first phase of the project the whole system will be oriented only to masonry buildings, and afterward extended to reinforced concrete buildings, monuments, life-lines and so on.

3. Deep knowledge expert systems

Research and development in the expert systems field have initially produced shallow knowledge systems, i.e. systems based on empirical knowledge, judgement, heuristics. These components represent only a part of the knowledge needed to solve problems in many fields (civil engineering is among these), and limits and problems of first generation expert systems have been clearly stated (e.g. [1]).
Second generation expert systems are trying to combinate shallow and deep knowledge (causal and algorithmic knowledge) (e.g. [2,3]).
This objective is pursued by the system described in what follows, through the creation of a model of the real world ("artificial world" [4]) which has its own structure and can exhibit behaviours. Either structural and behavioural models are hierarchically built at several depth levels [5].

4. The system architecture

The system is built on three main layers (fig. 1):

- model or artificial world;
- functions;
- man-machine interface.

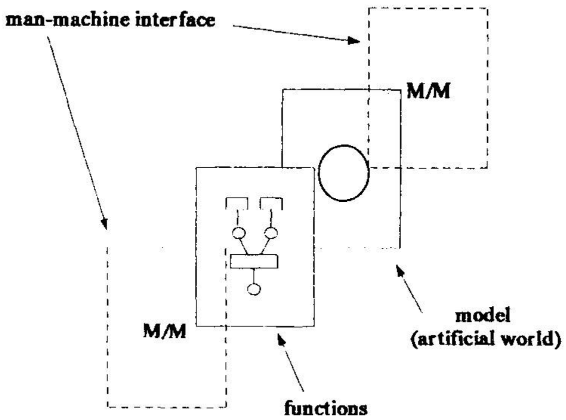

Fig. 1) System architecture

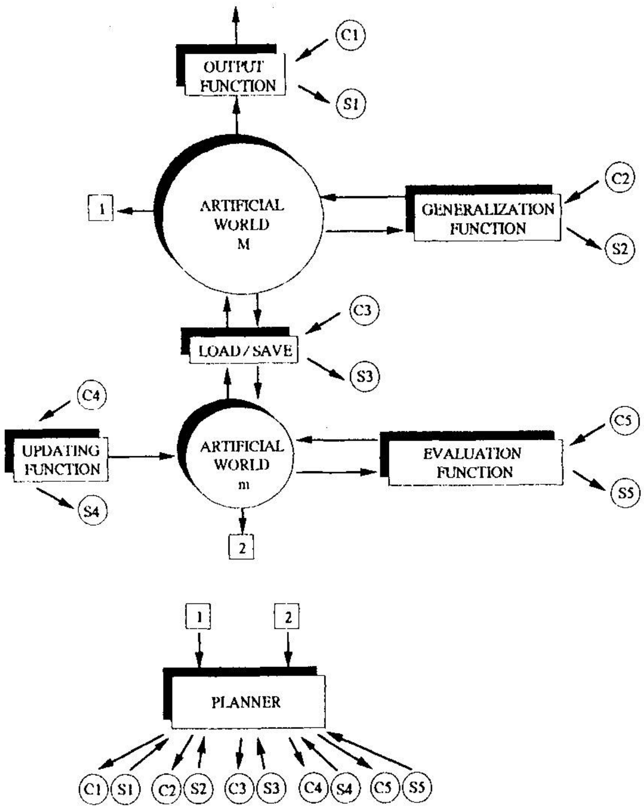

Fig. 2) Artificial world and functions

The artificial world depends on the case to be dealt with. For example it may be the model of a building, endowed with all the shallow and deep knowledge on structure and behaviour of the building itself, if the objective is the evaluation of the seismic risk of that single building, but it may represent the buildings of a village (or of a region) on the whole, as well.
In other words the constitution of the model can be seen as the implementation of a simulator through artificial intelligence software techniques.

The functions are possible operations related to the artificial world. Example of functions are:

- getting information from the real world to refine the model;
- simulating a seismic event on the model to evaluate the expected damage.

The man-machine interface allows the interaction between system and operator providing transparency to model and functions.

The structure of artificial world and functions are shown in figure 2:

- The artificial world "m" is a model of a single building and its environment.
- The "evaluation function" gets informations from "m" to produce a discussed risk evaluation together with a list of possible improving interventions and their estimated cost.
- The "updating function" modifies the attributes of the model "m" when more data are available either from observations, measurements, experimental tests.
- The artificial world "M" is a model of a class of building, modelled as a type building representing the class on the whole, subdivided into subclasses (different building types). Each single building is seen as a specific instance of one of the building types. Class, subclasses and instances are related through a inheritance mechanism; all the objects in the hierarchy have the same structure and the same potential attributes of "m" (fig. 3).
- "M" and "m" are related by a load/save function which can move objects from one to the other and viceversa.
- The output function allows outputs for the representation of "M".

Two last important performances of the system have to be mentioned:

- A generalization function can spread some attribute of specific buildings over whole classes or subclasses. This can be performed on statistical bases - when some information is available only for some building in a class, mean values can be generated and attributed to all other buildings - or on deterministic bases - if, e.g., an expensive experimental test has been performed on a building, some results may be attributed to other buildings recognized by a generalization algorithm -.
- A planner is making decision on data acquisition, evaluation, testing, numerical analysis, generalization of results, depending on budget, specific objectives and general seismic protections philosophy.
In other words the planner acts as the control panel of the system, being able of suggesting a strategy, activating all the system functions and collecting information related to the plan of action (through commands $C1 \div C5$ and status $S1 \div S5$ in figure 2).

5. The building model

As already pointed out the building model collects all the knowledge related to a building and its environment organizing it in the form of attributes which can be originated by observations and tests. Structure and behaviour of the system are also modeled at different depth level with hierarchical relations.
As a result the model can be represented by a point in a 3D space (fig. 4). Moving from one point to another one means to have more information or to use a more refined structure or to simulate a more complex behaviour.
Generally any movement requires the investment of funds, either to acquire or to manipulate more information.

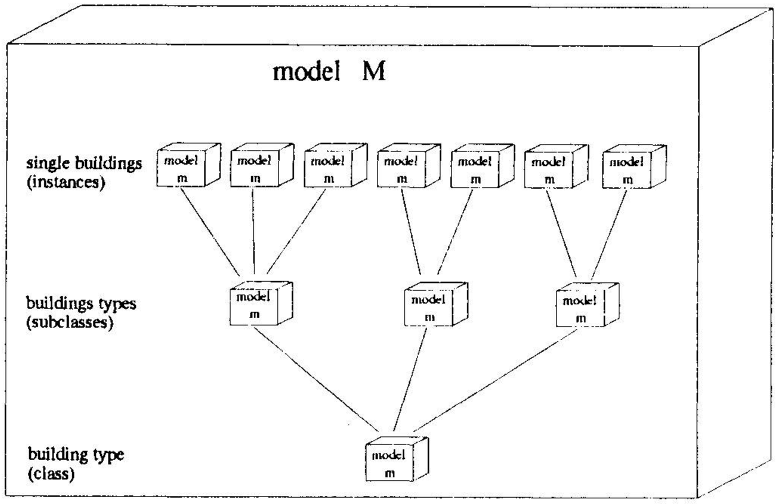

Fig. 3) The artificial world M

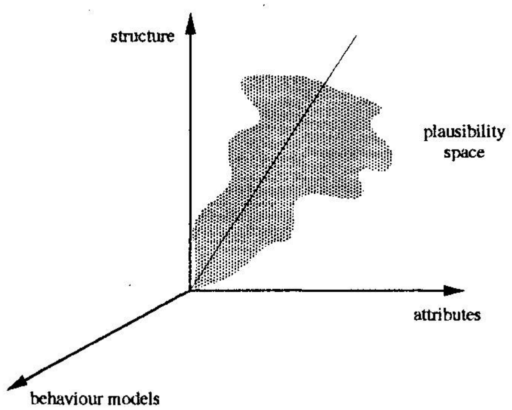

Fig. 4) The 3D space of the model

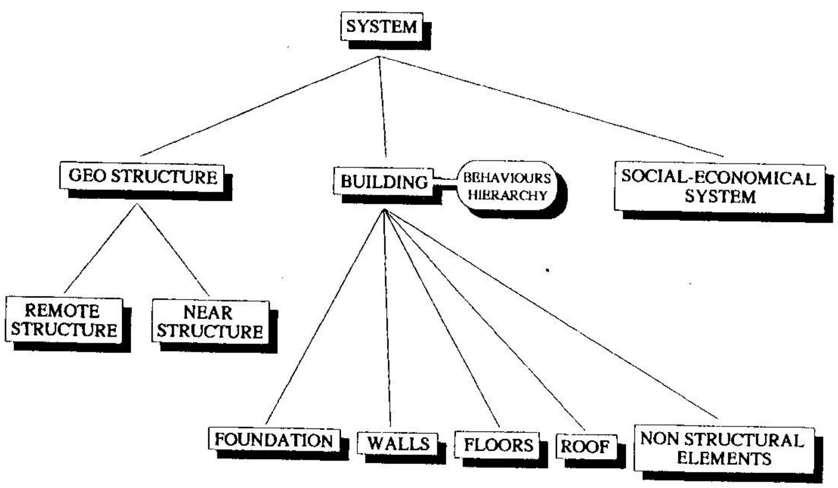

Fig. 5) The hierarchy of the structure

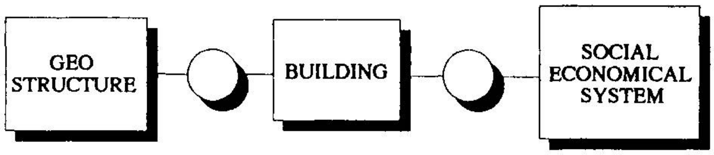

Fig. 6) First level of the structure

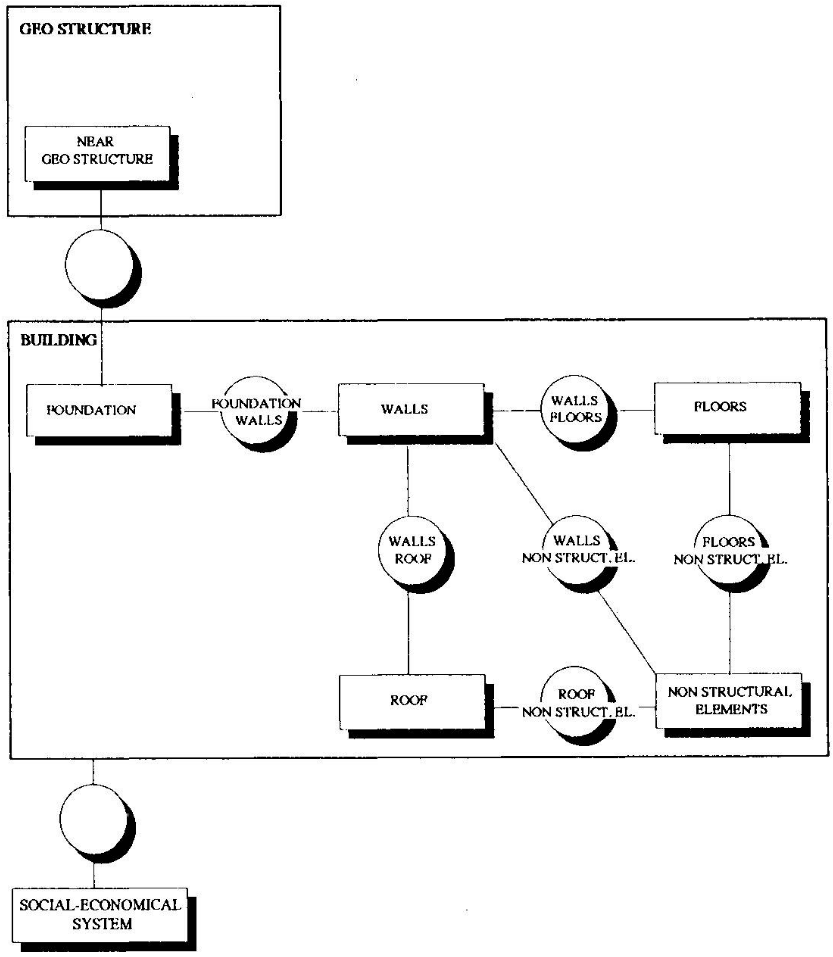

Fig. 7) Second level of the structure

Obviously it is not possible to reach any desired point in the space, but restrictions do exist (e.g. a numerical simulation might require certain quantitative data), so that the plausible space is constrained to a predefined shape, within which any movement will follows some suitable strategy.
The evaluation function can be applied to any plausible point in order to produce risk assessment and a discussion of the possible interventions.
It has to be stressed that shallow and deep knowledge are not synonymous of qualitative and quantitative knowledge (e.g. a deep structural model can be based on shallow attributes, or a numerical (deep) behaviour can be applied to a simple (shallow) structure.)
A simplified hierarchy of the structure itself is shown in figure 5. At the simplest level the structure assumes the form illustrated in figure 6; at a second level the structure is modelled according to what is represented in figure 7, where the "building" is decomposed into simpler objects describing his parts and the relations between parts; at deeper levels other decompositions have to be operated (e.g. a wall might be seen as an assemblage of vertical cantilevers and lintels and subsequently as an assemblage of bricks and mortar).

A behaviour hierarchy is associated to the object "building".
A hierarchy that can be used is shown in figure 8; again each level is subdivided into sublevels (qualitative and quantitative), where a major rôle is played by the constitutive relations used to model each element. Choices of primary importance are related to linearity and isotropy, static or dynamic simulations, damping, strain rate effects, unloading, stiffness and strength degradation, energy dissipation, failure criteria.

Attributes may be associated to objects at any level of the structure; some of these are automatically inherited by subobjects when a movement along the structure axis takes place (see figure 4). An example of a hierarchy of attributes for the object "wall" is given in figure 9; the first four levels apply to the building as a whole, too.
From the point of view of the constraints in the combination of different levels along the three axis some examples are given in what follows.

- For a representation of the structure at level one only the first and second behaviour level are applicable and only global attributes can be used.
  An example of such attributes are given in [6] (first level form), where they are all qualitative and coming from visual inspection.
- For a structure at level two a qualitative simulation of the elements can be combined with a computation of the shear strength on the base of global attributes, but it is possible to move along the attributes axis by asking detailed geometrical information or some experimental evaluation of the shear strength. On the behaviour axis four to seven levels (referred to figure 8) might be suitable depending on the attributes level.

6. The evaluation function

The fundamental approach followed in the risk assessment is the separation between simulation and evaluation.

The simulation activity covers the job of applying a seismic event to a building model (a point in the space in figure 4) to produce a possibly damaged model. This can be done for instance by a finite element simulation with a time history input, but also by a set of empirical rules which can produce qualitative damage on the base of qualitative attributes. An example of such rules are given in figure 10.

The evaluation activity is more complex, because it has to give a judgement on the output of the simulation activity.
This implies some definition of undesirable states, some definition of the distance between the present state and such limit states, some translation into economical values of such distances (social, historical, moral considerations are influencing this translation).
The evaluation has therefore to be performed through the following steps:

- simulating a seismic event, with the effect of generating new values of attributes;
- giving a judgement on the resulting damage, in a gravity scale;

1. rigid body
2. one degree of freedom (DOF)
3. one DOF per storey (rigid floors)
4. three DOF per storey (rigid floors, space structure)
5. walls and floor simulated by macro elements
6. walls simulated by finite elements, rigid floors (or macro elements)
7. walls and floors simulated by finite elements

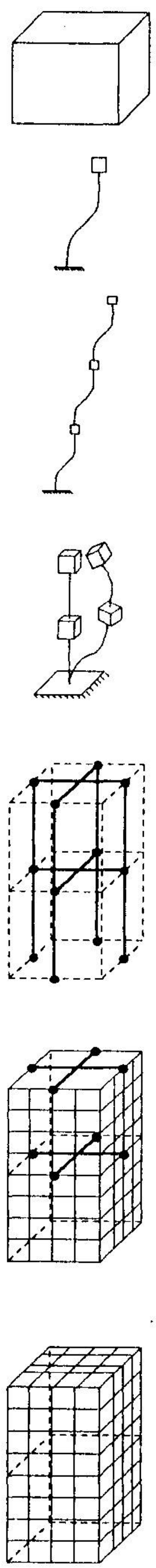

Fig. 8) The hierarchy of the behavioural models

1. Quality of the walls
2. Quality of the walls + total area
3. Total area + estimation of strength
4. Total area + experimental evaluation of strength
5. Geometry of each wall + estimation of strength
6. Geometry of each wall + experimental evaluation of strength

Fig. 9) Example of hierarchy of attributes

- **IF** good connections between walls
  THEN no damage expected
- **IF** bad connections between walls
  AND good connections between walls and floors
  AND stiff floors
  THEN no damage expected
- **IF** bad connections between walls
  AND good connections between walls and floors
  AND flexible floors
  THEN possible damage to the wall due to out of plane bending
- **IF** bad connections between walls
  AND bad connections between walls and floors
  AND stiff floors
  THEN possible failure of floors

Fig. 10) Example of qualitative simulation rules

- giving a judgement on the safety level (distance), in a safety scale, taking into account the attributes of the social-economical system;
- discussing the judgements on the base of the causal mechanism which generated them. The discussion is obtained going backward in the simulation.
  The discussion is important either to make possible to a human expert to check the "way of thinking" of the expert system and to give elements for another discussion, addressed at the next point;
- suggesting possible interventions, with their approximate (average) cost, using suitable bases of knowledge.
  The need of interventions is also discussed by comparing their cost with the cost of the expected damage, in terms of cost of repairing.
  It has to be kept in mind that different costs of retrofitting interventions might correspond to the same level of expected damage (depending on the damage mechanism).

7. The planner

The planner has two main functions, the first one related to the use of the artificial world "m", the second one related to the general strategy of the activities.

It has already been discussed that for a certain level of the model it is possible to evaluate the expected damage, the seismic risk and the cost of possible intervention.
It is obviously possible to obtain a more refined evaluation of all of them by new inspections, and/or experimental and/or numerical tests, but any possible refinement has a cost which can be quantified by entering the appropriate base of knowledge. Therefore the problem consists in deciding what is the benefit obtainable from a deeper knowledge in terms of probable reductions in the cost of the retrofitting interventions.
The main concept is that at a poor knowledge level the worst possible situation has to be adopted as true. On this base there is the probability that an increment of knowledge may allow a lighter intervention. Therefore the probable economical saving which can be obtained (evaluated by running again the simulation with a different starting situation) has to be compared with the cost of the new knowledge.
In conclusion the use of the artificial world "m" is governed by the principle of minimizing the probable total cost.
A secondary but important activity within this function consists of giving suggestions on the more suitable behaviour models depending on the available data (geometry, materials, stiffness, mass, connections, ...).

The second function has the purpose of suggesting the best strategy to be followed on the whole depending on objectives of the survey, budget, and again available data (number of buildings, expected damage, computed risk, ...). Clearly the strategy may be modified at each step of the procedure.
An example of a simple initial strategy might be as follows:

1. to perform a survey of all the buildings, getting only qualitative attributes;
2. to run simulator and evaluator using structure and behaviour at the simplest level;
3. to neglect the buildings with very low and very high risk for future testing (the meaning "very low" and "very high" depends on the budget);
4. to get more information for the other buildings;
5. to generalize information;
6. to run simulator and evaluator at deeper levels;
7. to choose the buildings on which it is more convenient to get more information on the basis of cost/benefit evaluation (the number of the buildings depends on the budget);
8. to repeat steps 4 to 7 until a certain level of reliability of the evaluation is reached or until no more funds are available;
9. to generate the final output.

8. Software engineering and development of the system

The system resulting from what has been previously described is a complex hybrid system, in which some parts are based on classic software techniques and some other are based on artificial intelligence techniques.
The problems in designing, developing and documenting such system are not different from the problems usually faced in software engineering.
The main choices for the development of the system have been as follows:

- the development process is based on step by step iterations on a prototype, with a series of phases for each step;
- at each iteration some chapter of a project file is generated or updated; all the documents related to the project are collected within the file.

The main chapters are:

- definition and modelling of the context of use of the system
- definition of the objectives
- modelling of the system with respect to the problem (independently on the implementation)
- translation into the implementation environment
- implementation
- evaluation

It has to be underlined that the modelling of the system does not depend on the specific knowledge representation techniques of the expert system shell that will be used. It is only in a second stage that the system model is translated into the specific languages (e.g. frames and rules).
A hypertext on a workstation will be the CASE environment for generating and updating the project file.
Petri nets are the base technique used to model the system; other techniques are used within the nets.

9. Conclusions

The system described is under development. A prototype which includes the building model, the evaluation function and the planner has been completed, so that risk evaluation and discussion of the possible retrofitting interventions are obtainable.
The system has been developed using the formalism of objects and rules supported by the shell Nexpert Object, on a SUN workstation with UNIX and on VAX station with VMS.
The prototype is being tested on the results of a survey on more than fifteen hundreds buildings, which has been originally performed on the base of the procedures proposed in [7,8].

10. Acknowledgments

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Expert System for Fire Vulnerability Analysis

Système expert pour l'analyse de la vulnérabilité au feu

Expertensystem zur Ermittlung der Brandgefährdung

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SUMMARY
In this paper we discuss the design and implementation of an expert system to estimate the fire vulnerability of a building. The expert system technique allows for a global approach taking into account people, environment and goods safety as well. Fundamental features like fire dynamics und building design process are integrated. Many techniques are combined to solve the complex problem production rules managing technico-economical constraints, weighted hypothesis trees dealing with uncertainty and tasks manager improving flexibility.

RESUME
Nous décrivons dans cet article la conception et l'implémentation d'un système expert destiné à l'estimation de la vulnérabilité liée à un bâtiment face au risque incendie. La technique des systèmes experts permet une approche globale intégrant la sécurité des personnes, de l'environnement et des biens. Des aspects fondamentaux tels que la dynamique du feu et le processus de conception du bâtiment sont aussi pris en compte. Différentes techniques sont combinées pour résoudre le problème: règles de production traitant des contraintes technico-économiques, arbres à hypothèses pondérées pour les analyses à forte incertitude, gestionnaire de tâches pour la flexibilité d'accès aux connaissances.

ZUSAMMENFASSUNG
Dieser Beitrag beschreibt Entwurf und Anwendung eines Expertensystems zur Abschätzung des Feuerrisikos von Gebäuden. Das System erlaubt eine gesamthafte Betrachtungswiese unter Berüchsichtigung der Personensicherheit, der Umwelt und der Sachwerte. Die Art der Baukonstruktion und die Branddynamik sind grundlegende Parameter. Zur Lösung des Problems werden verschiedene Techniken kombiniert: technische und wirtschaftliche Rahmenbedingungen sowie Fehlerbaumanalysen mit Gewichtung der verschiedenen Unsicherheiten.

1. THE PROBLEM

1.1 The Vulnerability concept

A discussion about fire safety evaluation needs at the begining a dialog frame setting. Within this frame we find a thematic object seen from different points of view as shown below :

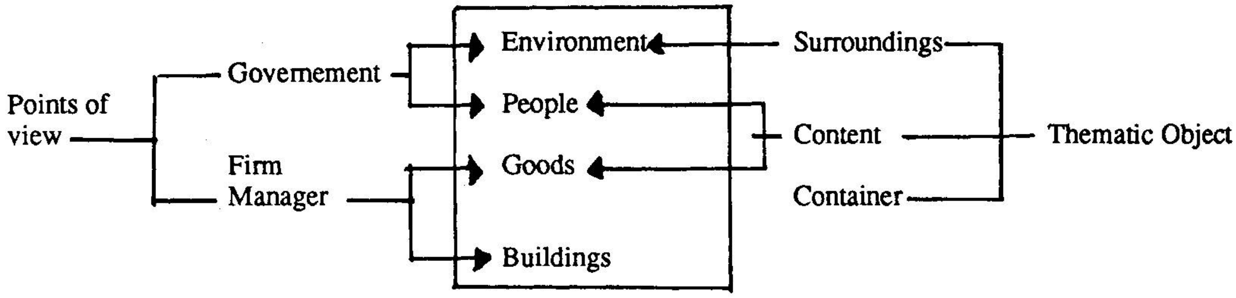


FIGURE 1

Goverments tend to concentrate on people and environment safety, while firm managers are more attentive about goods and building safety. However, even a restricted fire leaving the thematic object (people, environment, goods and buildings) safe can have a catastrophic impact on production and many indirect complications : loss of market place, penalties due to not respecting the terms of contracts. Those are manifestations of vulnerability. The more sensitive the thematic object the higher the vulnerability.

After a closer look it becomes obvious that the points of view are not divergent. A reliable government is indeed concerned with mastering different kinds of threats for people :
- whether direct, like injuries and deaths,
- or indirect, like unemployement and many other social impacts of an undesirable event. Governments sometimes must support a firm financially to avoid social disturbances.

On the other hand, firmes must preserve their standing and do not need to become unpopular because of careless attitude about employees and environment safety.

The fire vulnerability analysis is a systemic approach attempting to gather all points of view. Its field ranks from eliciting fire likelihood to forcasting probable impact on firm pereniality. It considers direct and indirect impacts, social, jurdicial and financial aspects. It is therefore more encompassing than fire safety analysis.

1.2 Today's solutions

1.2.1 Insurance approach

Insurance is probably the oldest kind of solution of the fire vulnerability problem. However it cannot be considered as a total solution for many reasons. Insurance policies have limitations. Some kinds of risks are not insurable. Insurance companies encourage their clients to take some technical measures (spinkler systems, fire resistant walls) and reduce the insurance prime accordingly. That leaves room for some optimization. Furthermore insurance does not solve the problem of people and environment safety.

1.2.2. Mandatory solution

In public buildings the problem is tackled by application of regular solutions. One of the major problems today with regulations is that their complexity and content is increasing. This is due to their too descriptive form. Another drawback is that sometimes there is no mandatory solution, since regulations are unable to forecast all situations (e.g. some office and industrial buildings in France).

On the other part, regulations are rigid and do not leave alternative possibilities to the designer. Though some non-regular solutions can be as good as mandatory ones and cheaper. It is because regulations do not give methods to evaluate the level of safety.
Finally, regulations do not care about reducing the cost effectiveness ratio and do not produce personalized solutions (i.e. suited for the actual risk).

1.2.3 Technical approach

A better knowledge on materials and fire behavior allows for scientific approachs today. There are several main features in a technical approach :
- the fire model used can be :
* deterministic : the fire is supposed to occur and the systems involved in controlling its development and propagation are supposed to work when needed as planned.
* probabilistic : the fire has probabilities of occurence, development and propagation. The control systems have a failure rate.
- the thematic object model can be :
* holistic : if it uses nominal classes for building materials and people. Nominal classes are described by a small number of attributes which many of them have a fixed value obtained from statistics.
* atomistic : if building, materials and people are modelised as systems described by parameters. There is no *a priori* value for those parameters.

Technical solutions can be difficult to apply because of a great number of sub-fields to manage. It is indeed technically possible to reduce fire risk by :
- architectural means,
- constructive means,
- mechanical engineering,
- fire detection,
- alarm managment,
- human organisation,
- people evacuation,
- smoke control,
- fire extinguishing systems .

Some of them are competitive (e.g. smoke control and sprinkler controversy). Moreover those sub-fields involve a great number of professionals from different areas with different working practices to coordinate :
- architect, civil, heat and accoustic engineers for the building field,
- safety engineer, fire brigade for the safety field,
- fire fighting materials constructors,
- insurance companies,
- tests laboratories,
- control offices authorized in supporting the local authorities when mandatory solutions are involved.

From a technical point of view the fire safety domain is too large for one man to manage. As a result there is no human expert able to operate at the global level. This has lead to sub-field limited solutions. Worse, those solutions are often introduced after the design process, since the architect works alone. So they are more expensive and less efficient.

As a final note the sub-field limited solutions generally do not take the dynamics of the fire phenomenon sufficiently into account.

2. A SOLUTION

2.1 Overview of our global solution

According to the intrinsic deficiencies mentioned above, an expert system based only on regulations (though useful) does not solve the problem. A technical and global approach is possible as we will shortly show.

A global approach implies a number of features :
- opportunity of action for all of the professionals concerned,
- a model of the fire dynamics,
- a model of the thematic object,
- a model of the thematic object evolving.

We have chosen :
a) a midway solution for the fire model between deterministic and probabilistic. The fire is considered in three states :
> state 1 is ignition : the fire begins in a small region of a room,
> state 2 is development : the fire grows to the room size but is restricted to this area,
> state 3 is propagation : the five leaves the ignition room.

The initial state is numbered 0 (no fire). So we have three transitions to consider : state 0 to state 1 and so on. Each transition is supposed to have identifiable causes and impacts, and there is specific measures to reduce them.

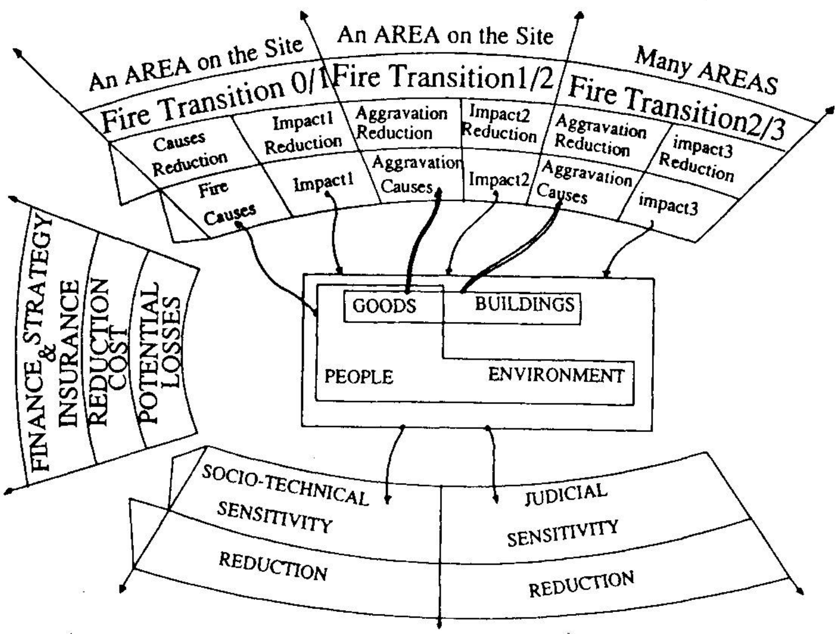
People, goods and environment can initiate the fire. This initial fire can then threaten people, goods, environment and buildings. Therefore we must have specific meausres to reduce both the causes and impcts of ingnition.

Goods and building can favour the development and propagation of an initial fire. During theses fire transitions all entities can be threatened. Here again we must have measures to reduce causes and impacts of aggravations.

People, goods, buildings and environment have an intrinsic sensivity. An entity is a highly sensitive one if a small disturbance can have a significant impact on it. It is the reason why, for us , the term risk refers to a couple hazard-sensitivy.

b) a systemic model for the thematic object : the system is the site in which we find buildings, goods and people. The environment of this system is composed of the site surroundings, the atmosphere and the substratum.

To take into account the evolution of the thematic object we consider three stages :
> stage 1 is the rough plan,
> stage 2 is the project,
> stage 3 is the built object.



Overview of the Global Approach
FIGURE 2

Vulnerability evaluation and measures to reduce it vary with the thematic object stages, except for sensitivity. we have a scheme like figure 2 for each stage, this is what is shown in figure 3.

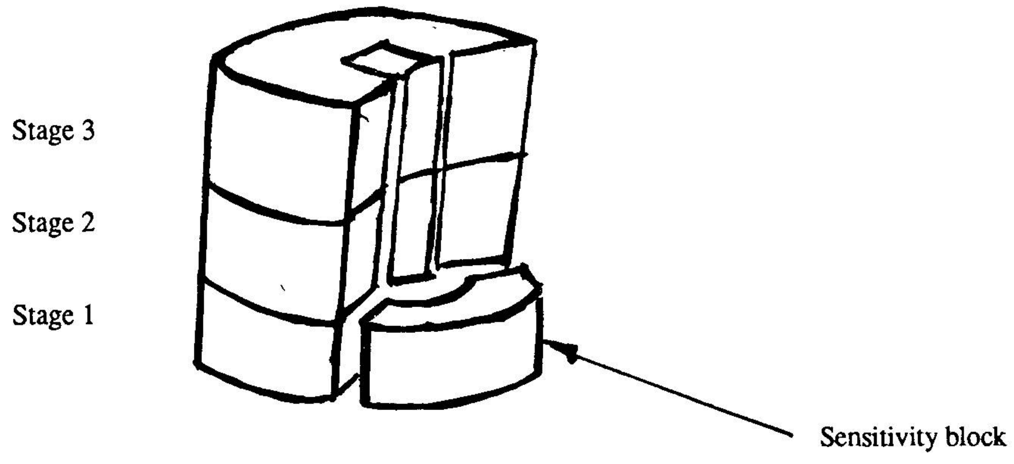


FIGURE 3

The functional aspects of the thematic object in terms of :
- MISSION : one of the major purposes of the firm, e.g. car manufacture,
- FUNCTION : one of the main tasks necessary for a mission, e.g. communication
- ACTIVITY : low level task necessary for a function, e.g. photocopy, raw material conveyance.

2.2 Strategy for the global solution

a) Identification and estimation
- identifiy sensitive entities (people, activity, ...) and their geographic location,
- identify hazard factors (people, goods, environment, ...) and their geographic location,
- superimpose the two resulting maps to see hazard and sensitivity proximity,
- determine entities that need hazard or sensitivity reduction,
- estimate the expected losses related to the selected entities.

b) Prevention and protection measures
For the selected entities consider :
- mandatory measures,
- alternative measures.

c) Financing studies
- estimate the cost of all measures of risk (the couple hazard-sensitivity) reduction
- estimate the cost of insurance in two cases :
    * with measures of risk reduction,
    * without measures of risk reduction.
- using these different cost estimates (expected loss, reductions'cost, insurance cost) apply a financial method to see which solution is the best among :
    * increase the technical measures,
    * take an insurance policy,
    * put money aside (auto-insurance),
    * or a combination of the three possibilities.

This strategy is applicable for each fire transition and each stage of the thematic object. But the knowledge used differs.

3. WHY AN EXPERT SYSTEM

Obviously the global solution is a complex task. It involves managing a massive knowledge with many symbolic parameters. Moreover this knowledge is open to improvement, since it is not well formalised. There is no global expert but there are experts able to submit their knowledge relative to each sub-field (cf. paragraph 1.2.3). Those reasons have guided our choice of a multi-expert system solution.

4. ABOUT THE KNOWLEDGE AND ITS REPRESENTATION

4.1 Categories of knowledge underlied by the global strategy.

4.1.1. Identification and estimation

Identify an hazard and estimate its likelihood and consequences is a predictive task. Therefore it involves dealing with past and future of a system with incomplete and unreliable data. Prediction involves also contingent reasonning.

4.1.2 Prevention and Protection

Preventing an hazard occurence and selecting suitable protection measures are design tasks. They imply keeping track of many constraints, dealing with spatial relations and normative (taken as certain) data. Design involves tentative and qualitative reasonning. The solution space is large and continuous but it can be abstracted because of the scale effect.

4.1.3. Financing

Financing hazard reduction measures and insurance solutions are planning tasks. The need to take the future into account leads to incompleteness and unreliability in data. It is also necessary to proceed by a tentative, contingent, non-monotonic reasonning. In spite of a large solution space there are a few reasonnable solutions. As in design and for the same reason the solution space is abstractable.

4.2 Knowledge representation

4.2.1 Weighted hypothesis trees (WHT)

For the predictive tasks such as hazard or sensitivity identification, fire impact estimation, we have used weighted hypothesis trees. A WHT is a tree whose nodes are hypothesis weighted by a conditional distribution. The conditionning factor is the confidence allowed to the hypothesis. Confidences are real numbers comprises between 0 and 1. Weights are real numbers ranked from 0 to + . Figure 4 below shows an example of distribution for one hypothesis.

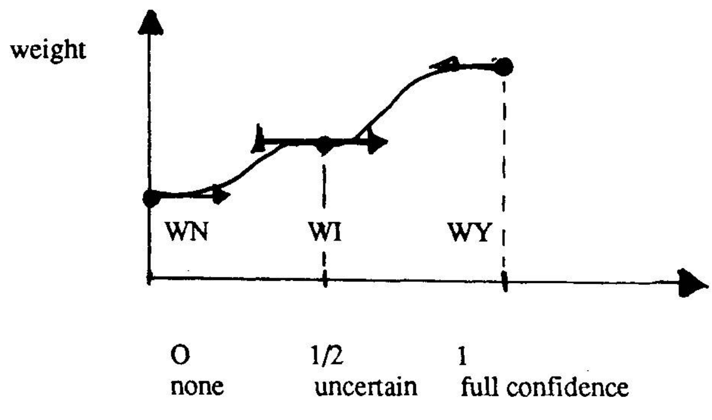


FIGURE 4

WN, WI, WY are subjective values given by an expert pannel. The confidences of terminal hypothesis are given by the end user. For non terminal hypothesis the confidence is evaluated according to the kind of node :

- AND node

let H = (H1 AND H2 ... Hn)

each Hi has a matrix distribution (w_{ij}) , j = 1,2,3.

$$\text{confidence}(H) = \prod_i w(H_i)/w_{max}$$

where $w_{max} = \max_{i,j} w_{ij}$. $w(H_i)$ is the current weight of Hi according to its current confidence. Π is the product operator.

- OR node :

let H = (H1 OR H2 ...Hn)

with the same definitions of w_{max} and $w(H_i)$,

$$\text{confidence}(H) = \prod_i (1 - w(H_i)/w_{max})$$

4.2.2. Rule base

For design tasks such as setting prevention and protection measures we have used a rule base approach. The production rules used can be classified in two categories :

a)- rule for solutions proposition :

Assuming that the context is a room and the action the expert system wants to perform is a proposition about the kind of smoke control to install, a rule can be :

rule smoke 50

IF the number of storeys above the room is > 1 and

the room is not located in an underground zone

THEN the type of smoke control ="NATURAL INLET AIR , MECHANICAL EXHAUST AIR

A more sophisticated form of this kind of rule is those using alternatives. For example

IF .... <same conditions>

THEN alternative solutions :

1.- the type of smoke control ="NATURAL INLET AIR , NATURAL VENT" (prf : 5, 10)

2.- the type of smoke control = "NATURAL INLET AIR , MECHANICAL EXHAUST AIR" (prf : 10,7)

END

b)- rules for solutions evaluation :

Typically this kind of rule involves alternative constraints. For example, assuming the context is a staircase and the action needed a verification :

IF the number of doors by floor > 6

THEN alternative constraints :

1.- the stairshaft is enclosed (prf : 10, 7)

2.- All the corridors leading to the stairshaft are partitionned with 1/2 h fire doors (prf : 8, 10)

END

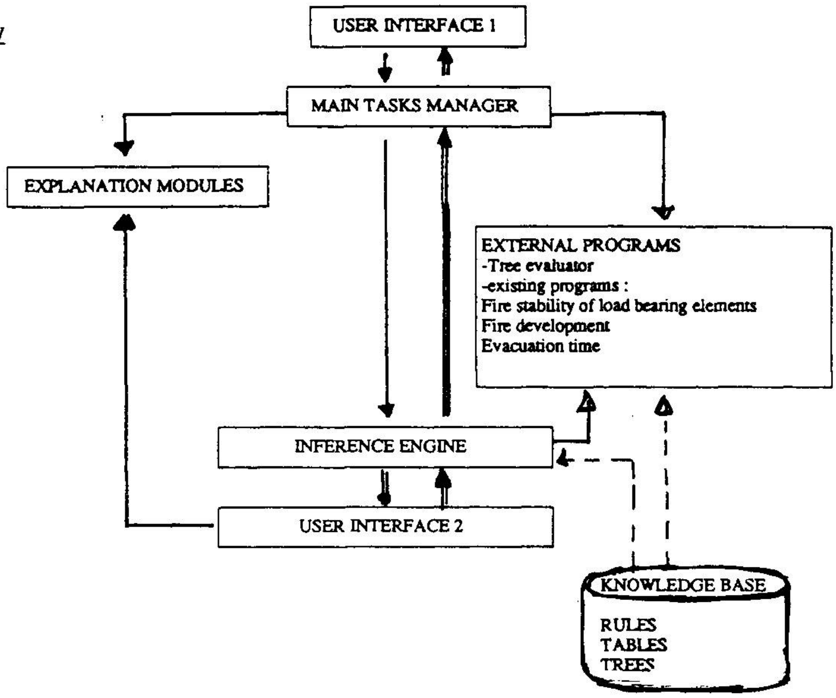
In the above rules prf : denotes experts' preferences about the solutions. The first number indicates the level of technical preference and the second gives the level of economic preference. Preferences can be combined in three ways :

* Technical tendance : sort alternatives by decreasing technical preferences,
* Economic tendance : sort alternatives by decreasing economic preferences,
* Optimizing tendance : sort alternatives by decreasing ratio economic/technical preferences.

Alternatives constraints or solutions can be propagated. This is a tentative reasoning strategy i.e. alternatives are selected one by one regardless to experts' preferences. The solutions or constraints having lead to the best global performance are then chosen.

5. SYSTEM DESCRIPTION

5.1 Overview



* existing programs

Fire stability of load bearing elements
Fire development
Evacuation time

FIGURE 5

5.2 Components description

- the main tasks manager insures project management : selects knowledge base, calls inference engine, calls external programs, solves inference engine deadlock,
- the explanation modules : show the rule under consideration, or the current goal, paraphrase questions,
- the user interface 2 : stops the inference engine or the session, submits explanation requests to the Explanation module, prompts the user for parameter value,
- the user interface 1 : calls main task manager, browses rules and deductions, selects goals, modifies parameters,
- external programs are any executable ones.

By now the knowledge base contains 20 separate rule bases of 10 to 60 rules each, 3 tree files totalizing about 150 hypothesis.

6. SYSTEM DEVELOPMENT

6.1 Development steps

We have followed the classic steps : identification, extraction, formalisation, implementation, test. The validation step is not yet considered.

- Problem identification : a pannel of eleven experts covering all of the sub-fields guided by a knowledge engineer has setted specifications. A work plan has been established which specifies which experts gives what knowledge. This has lead to sub-groups of two or three experts. Plenary meetings were forecasted to insure feedback interaction,

- Extraction : the knowledge of each sub-group of expert has been collected in a cyclic process (from sketch to more refined knowledge). For subjectivity prone knowledges seminars of about two or three days were organized and methods to reduce biaises were used.

- Formalisation : the knowledge has been translated in many forms, rules, tables, procedures, weighted hypothesis trees,

- Implementation : using an ad hoc tool we have feeded the knowledge in a microcomputer

- Test : In addition to the immediate tests done by the knowledge engineer we have forecasted more realistic tests. Five copies of the experimental expert system are submited to five different experts for improvment. This is the reason why the implementation tool must accept knowledge in a natural language form and allow flexible access to the knowledge during a session.

6.2 System organization

<u>6.2.1. Overview</u>

As shown in figure 6 the domain has been divided into fields, themselves divided into sub-fields. Sub-fields are described by logic factors which are high level information (e.g. building geometry) supporting the global judgement. So they have a level of confidence to determine. This is achieved by reasonning about lower level information : the parameters (e.g. building height).

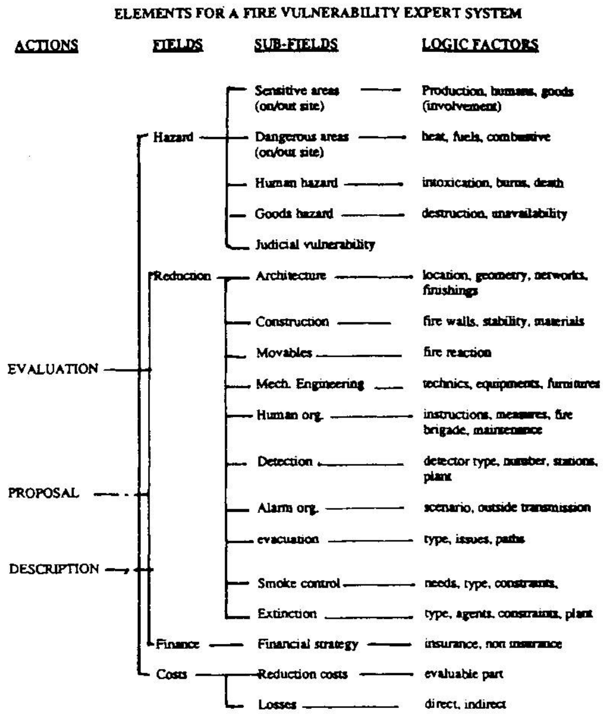


FIGURE 6

Actual system behavior is obtained by operational goals. These are specific actions on a specific logic factor (e.g. propose a smoke detector type).
The thematic object and its functionnal aspects are put in concerete form by entities called contexts : firm, site, environment, building, room, activity, fire brigade are examples of contexts. An operational goal involves at least one context (e.g. propose a smoke detector type for a room).

6.2.2. System modules

Logic factors are put in separate modules that are trees or rule bases for three reasons :
- since there are many experts, it is necessary for each of them to manage his own knowledge only during improvment sessions,

- the end user may want to check only a specific point. Therefore it is necessary to allow him to go straight on the needed expertise. This is what we call focused expertise.
- this improves the efficiency of the inferences as well as the rule base testing.

6.2.3. Modules interactions

There is a graph, as in figure 7 below, for each building stage and for each fire transition. These graphs represent the way many kinds of knowledge interact. For example in figure 6 the double arrows show what hypothesis will be modified in the WHT (in terms of distribution) according to the confidence determined for a specific logic factor.

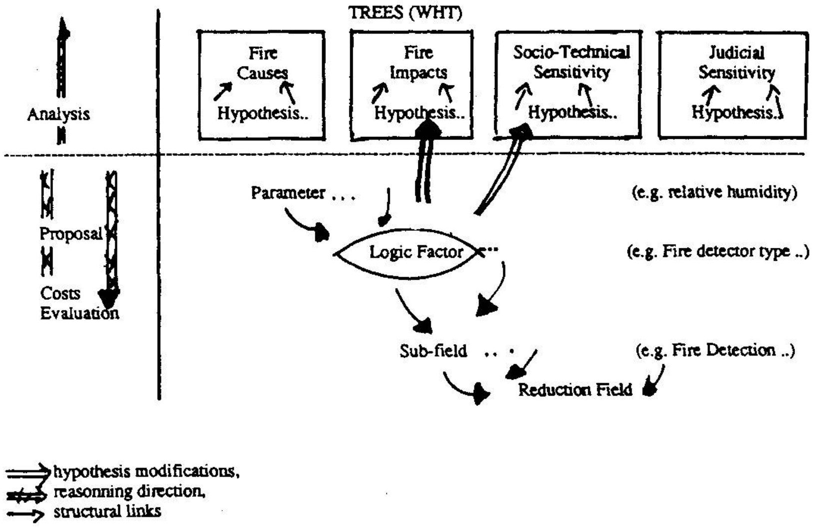


FIGURE 7

There are also interactions between logic factors (not shown in figure 7). For example :
- two logic factors are competitive if the performance of one tends to diminish the other's. Proposal about such logic factors are postponed, as late as possible.
- a logic factor can depend on another. It is then suggested to look at the first before the second.
- a logic factor can compensate another. If the confidence of one is too low we can try to raise the confidence of the other.

All of these interactions are used to guide the global reasonning.

7. ON GOING WORK

The current experimental system achieves focused expertise. We are implementing the global reasonning. The tool used primarily, a 0+ inference engine, is too weak for the global reasonning so we have turned our attention to object oriented environments. That kind of tool should allow us to implement semantic nets on the contexts, and specific behaviour of contexts. Furthermore we have planned to take advantage of access to data bases and realise a coupling with a graphic interface. This should lead us closer to the architect's world.

Economical and technical supports :

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CERBERUS GUINARD : Detection systems manufacturer,
FEDERATION NATIONALE DU BATIMENT : French building federation,
SAGERI : Insurance broker,
VERITAS : Control office,
CENTRE TECHNIQUE ET INDUSTRIEL POUR LA CONSTRUCTION METALLIQUE : Tests laboratory,
ESPACE TECHNIQUE : Design office.

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Noé: Expert System for Technical Inspection of Waterproofing on Flat Roofs

Noé: système expert de contrôle technique de l'étanchéité des toitures terrasses

Noe, ein Expertensystem für die Kontrolle der Wasserdichtigkeit von Terrassendächern

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SUMMARY
Within the framework of feasability study the Centre Scientifique et Technique du Bâtiment (CSTB), has jointed together with a technical inspection organisation the Centre d'Etude Technique des Apaves, to elaborate an expert system prototype to simulate technical inspection work applied to waterproofing work on flat roofs. Stimulated by the results of this application, we can already envisage the interest for an expert system shell specifically for technical inspection, and also we look at the way to use it for teaching and deisigning.

RESUME
Dans le cadre d'une étude de faisabilité le Centre Scientifique et Technique du Bâtiment (CSTB), s'est associé à un organisme de contrôle, le Centre d'Etude Technique National des Apave, pour élaborer une inaquette de système expert de contrôle technique relative au sous-domaine de l'étanchéité des toitures terrasses. Les résultats encourageants de cette réalisation nous permettent d'imaginer plus globalement l'intérêt d'un générateur de système expert d'assistance au contrôle technique, ainsi que l'extension du système vers des utilisations plus variées, telles que l'aide à la formation des contrôleurs techniques ou encore à la conception des ouvrages d'étanchéité.

ZUSAMMENFASSUNG
Diese Studie hat den Zweck, die Machbarkeit eines Prototyp-Expertensystems zur technischen Prüfung der Dachterrassenwasserdichtigkeit abzuschätzen. Die Originalität eines solchen Systems besteht darin, dass sie den Vorgang des technischen Kontrolleurs sowohl in der Abwicklung der Kontrolloperation als auch in ihrem eigentlichen Wesen wiedergibt. Die ermutigenden Resultate dieser Forschung erlauben es, weitere Werkzeuge für technische Kontrollen für Lehre und Entwurf zu verwirklichen.

1. INTRODUCTION

1.1 Technical control, what for ?

Technical Control is a human activity intended to verify that a project, either at a preliminary stage, when implemented, or even at completion time conforms to a set of well defined specifications. This brief definition already illustrates some of the most challenging properties that an expert system should account for in order to reproduce the step of controller.

First of all, the process implies a peculiar kind of logic seldom used by most programming habits, referred as temporal logic [1], [2], [3], devoted to the modelling of concurrent or successive interdependent events, in so far as the process spans over time and the project must be controlled during incremental phases leading to the final configuration.

The second difficulty is tied to the control activity in itself, as it can be considered as the reciprocal function of design, an area where a lot of work has instead been accomplished.

From the designer viewpoint, getting a suitable response to a problem can be described as a sequence of actions that aims to transform a set of initial specifications into a valuable assembly of objects, recognized as a solution [4], [5]. On the other hand, the technical control services given by experts have been less studied by scientists, mainly involved in this research area with plants or industrial control process.

1.2 Legal context

Thus, the field covered by this paper, technical control carried out by human specialists and viewed as an intellectual practice based on experience, is still rather an unexplored area. In this domain, the controller takes the result of a design, an intended use to be reached, and tries to determine if the overall set of constraints has been respected following the inverse path of the designer. The model developped by [6], states that constraints can be classified according to three main characteristics: the properties of the constraint generator (introduced either by the conception process, the customer, the end-user, or by legal requirements), a domain (among internal or external including the environment of project), and the underlying functions (practical concerns, functional, formal or symbolic).

This project deals with the stronger set of constraints aforementioned, as we wish to model the state of the art rules encoded within different unified codes of practice, considered as the regular documentation to be used. Nevertheless, even for this restricted context due to coercive legal clauses, many alternatives can be encountered by the designer, and an automated rule-based control process involving pragmatic knowledge to assess the changing reliability over time of an evolving proposal is a difficult task.

The Noé expert system is a practical software dedicated to a narrow field within the wide area of technical control, and aims to account for the technical inspection of waterproofing on flat roofs, at the different epochs of the project's life. This selection was due to the high contribution of the various waterproofing techniques to the global percentage of observed building damages.

2. COGNITIVE APPROACH

2.1 Task analysis

The first objective in developing such a system, was to observe the behaviour of the human controller, and to build a model of the tasks to be carried out so as to account for the intended activity. This analysis had to split the controller's work into separate phases, from a temporal viewpoint, and to associate for each of them a semantic model of the goals pursued.

This was easily achieved, in so far as the controller primarily acts as soon as the first drafts can be obtained for the project, then reviews the proposals made by selected firms to implement some solutions among a wider initial set, and finally inspects the working site at the end of the installation of the waterproofing layers and of the related protections. This incremental involvement of the control process gives the general framework to be modelled by the software, and the system should of course reproduce such a temporal logic, as the information flows obey this sequence.

At the beginning of the project, the framework is still ill defined, and many solutions can be accepted according to the intended use; this step will be referred as "design level". Then, depending on the successive refinements of the design, and of the products retained for the effective installation, the controller verifies that responses made by firms are correct at the proposal level; this will be curiously referred to by specialists as the "execution level", even if the effective installation of the waterproofing system is only done later on. Finally, when the system is installed on the work site, leading to an "in situ" control, we talk of the "installation level". This terminology is important, in that it will be used throughout this paper, and as it helps to give a frame to the software functionalities.

Each of these separate phases leads to a specific analysis, involving dedicated knowledge bases, designed to produce successive regular reports, such as the preliminary report, intermediate report, end of phase report. For each of them, careful observations are produced and should be interpreted at three different semantic levels. The observations are defined as follows: prescriptions correspond to compulsory alterations to the intended design and represent the most coercive action given by the controller as they arise when a regular guiding rule is violated, recommendations offer well known solutions that should be substituted to an odd but not irregular design, and finally advice has an indicative meaning coming from well tried concepts. These reports are produced at three monthly intervals and in the meantime the project evolves from a pure design phase to an operational waterproofing system. The general activity of the system, and the different phases previously noticed can be summarized by Fig 1.:

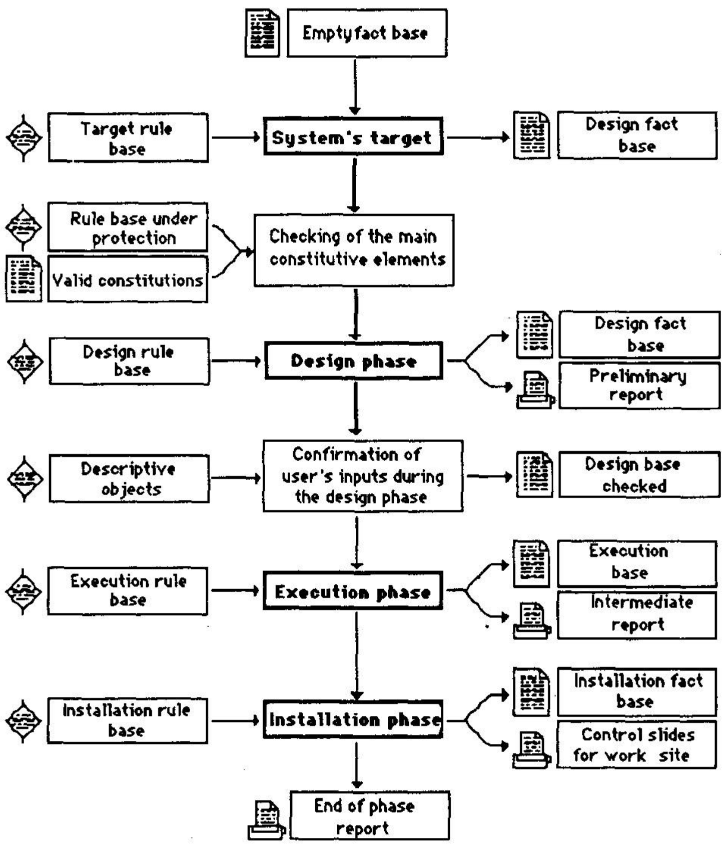

Fig. 1: The general task organisation of the Noé system.

In Fig. 1, we see the three main phases of the control cycle of the software (design, execution and installation phases) , and moreover an initial plan to determine if the problem described by the user is within the system's scope, (i.e. the competence domain of the program). If this assertion is verified, the system controls the correctness of the submitted preliminary design (no unrecoverable errors in a compiling analogy), and if it is correct enables the scheduling of the real design phase (considered from the controller's viewpoint and not from the designer's), for which prescriptions, recommendations, and advice are given. A preliminary report is then produced.

As some delay can occur before execution takes place (i.e. analysis of the responses transmitted by firms), a general checking of the overall properties previously determined is performed. If inconsistancies arise, the culprits are suppressed from the fact base, and the control is transferred to the first rule base (i.e. target rule base) to reconsider the problem. When the design can be submitted to the execution module (i.e. no subsequent noticeable alteration to the initial ordering was observed), the execution rule base is activated and leads to an intermediate report, including more detailed instructions than the preceding ones but dealing with the same scope.

Finally, when the waterproof coverings are installed, the system produces checking forms to be used on the work site to ensure the final checking of the waterproofing system and to guarantee its conformity to the unified codes of practice.

2.2 Consistency checking

Some difficulties arise from these overlapping phases, and we modelled the induced consequences that have to be taken into account when some important alteration occurs to the original design. A semantic network of linked objects is managed by Noé so as to propagate the effets of changes that imply modifications or suppressions of the consequents futher altered by reasoning. This problem is rather similar to truth maintenance functions [7], [8], [9], [10], where the origin of inconsistencies comes from the temporal evolution of the environment, some properties being transformed when controlled by the expert. This topic is encompassed by Mc Allaster [8], and temporal consistency has long been a privileged area for Truth Maintenance Systems (TMS). We developed a simplistic framework, where any significant change is propagated to the consequents and where dependent objects from the modified node (a node refers to any transition for which a value is either asked or computed), are suppressed from the environment and should be recomputed. This is quite a radical approach, but it ensures the integrity of the database even if it is quite resource consuming.

Sophisticated models could be introduced such as a complete TMS, or a constraint-based language [11], but for the first implementation of the system we followed a pragmatic approach, for which each object is tied to its consequents thanks to semantic links (recognized and defined by the designers of the application), and any alteration of fundamental properties of antecedants induces the removal of the consequents and enables the triggering of previous rules.

The following network reproduces a very small subset of the overall semantic links modelled by the Noé expert system, and illustrates in a schematic way some interdependencies between the considered objects. The time variable does not appear in this view, but it intervenes for each one of the phases previously described (and especially during the design level), and between two successive steps as some alteration to a predefined organisation may occur. An historical recording of the order in which the inferences have been accomplished is stored (without possible concurrent paths as in [12], [13], [14], [15], [16], [17], [18], [19], and is used to remove the consequents when a support node has been altered during the checking phase (i.e. either the designer suppressed on its own a property or a modification suggested by the controller induced the transformation and the related coherence processes).

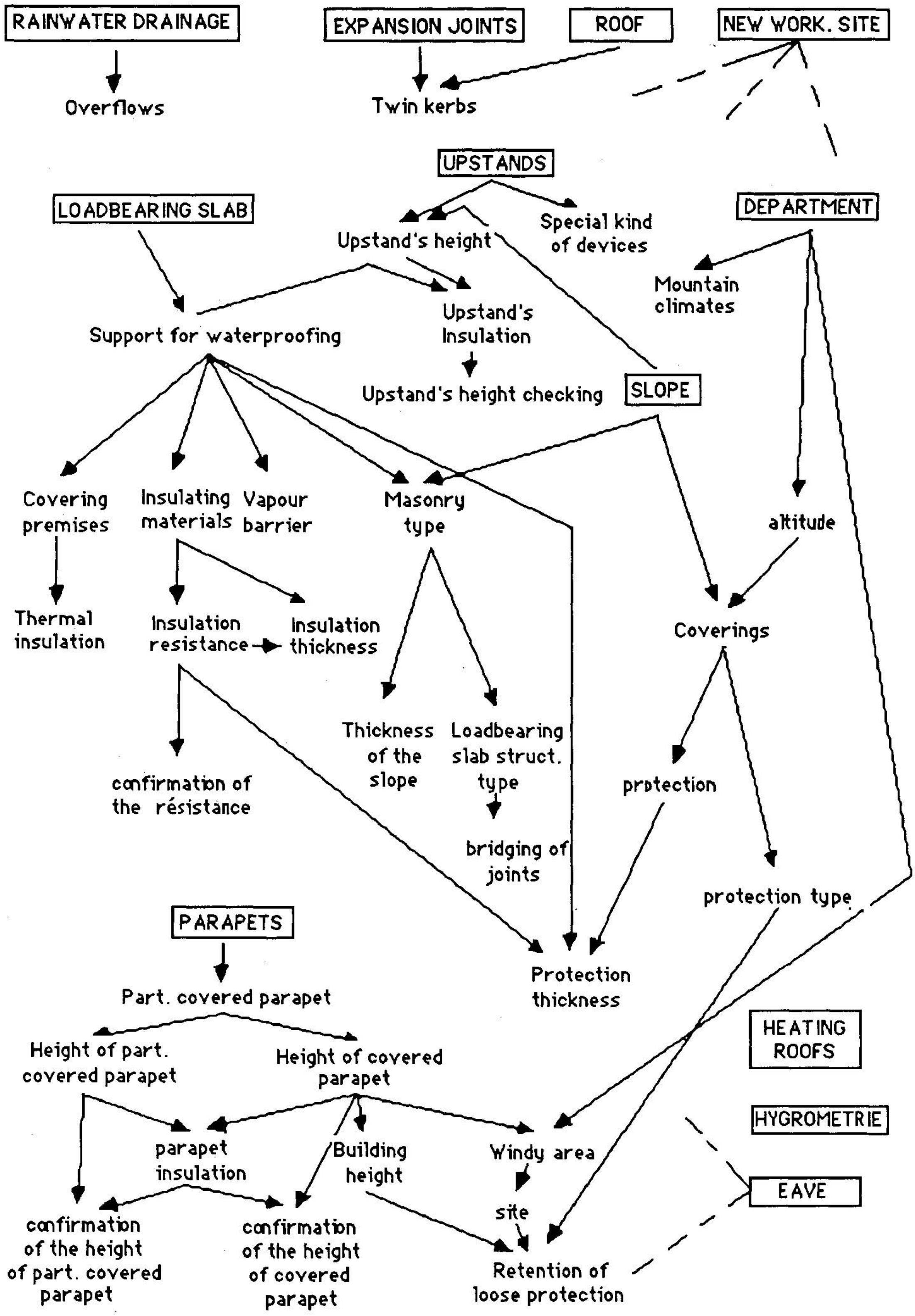

Fig. 2: A subset of the overall semantic network of interdependent objects.

The links are explored and the creation time of the encountered objects is tested to take legitimately the destructive decisions. This principle is illustrated in Fig. 2, support nodes appearing in the higher part of the graph, and consequent nodes being linked with arrows. The real network involves one hundred and sixteen objects connected thanks to the link property of the object model we use. In fact it will be noticed that among this set of objects, some could be better considered as slots of higher level frames, that we are currently beginning to implement for Noé.

In section 3, the choices made for the current implementation will be justified, in relation to the supposed end-users we aimed to reach, and their potential hardware (mainly restricted machines with approximately one mega byte).

3. SYSTEM ARCHITECTURE

3.1 Introduction

A severe restriction to the design of the system architecture was introduced by the kind of hardware on which it should be used. The Machintosh was initially chosen as a valuable target for the system as it is widespread within the waterproofing corporation (i.e. firms, architects, manufacturers). But it should be noticed that for basic machines, a memory of one or even two megabytes is a narrow space to implement a complex system. So we used basic Lisp mechanisms, a primitive object layer not too resource consuming, and the powerful intrinsic graphical functions of the Machintosh based on the I/O Trap of the ROM.

Of course, this framework is evolving so quickly, that our focus is now moving toward virtual concepts, including virtual machines (i.e. the LLM3 virtual machine of Le-Lisp is a good example of this concept), virtual graphical solutions (the virtual bitmap of Le-Lisp responds to such an objective) [20], fully portable interface builders from one hardware to another, using different windowing systems (i.e. the Aïda toolbox is such a kind of powerful image manager) [21], and abstract software components (i.e. only defined by an abstract structure and their associated behaviours).

The implementation strategy retained nevertheless enables us to broadcast the system to a wider public, as it does not require any specific machine or advanced underlying software; Noé is self-contained.

3.2 Reasoning model

The reasoning model of Noé is very straightforward and implements a forward chaining strategy directed by the facts to be checked. For each reasoning phase previously described, a specific rule base is triggered, the one in charge of this verification level, and is processed in a standard way by the inference engine.

The principle used is that for each base submitted, the engine scans the sequence of rules and determines if at least one of them is to be fired. If so, the rulebase will be considered again (i.e. some other rules can have their status changed by the inference results added). The inference cycle is stopped, for the considered rulebase, either when no rule is left in the agenda, or when an explicit fork is made to another rulebase. The inference engine in itself is a simple function taking as an argument a rulebase. This enables the system to chain the rulebases, as the action of any rule can schedule in a recursive way the next rulebase to be examined in the new context recognized by the premisses.

3.3 Knowledge representation

The knowledge managed by the system belongs to three distinct types: objects, rules, and facts. This is a conventional way of representing knowledge in most expert systems, and we did not develop any original feature in that respect. In fact, we tried to find economic memory allocation policies (§3.1.), using rather low level primitives, even if the limitations induced sometimes could be deemed as restrictive.

3.3.1 Objects

Objects, better entitled entities, are implemented at a very low level, using directly Lisp symbols and attaching them properties thanks to the basic property list mechanisms (P-Lists). It ensures a very efficient functioning, as it corresponds to low level *wired* Lisp faculties, and enables a set of data to be packaged within a memory structure. It lacks some obvious features of real object based environments [22], [23], [24], but was deemed satisfactory for the specific goals encompassed by the prototype. Nevertheless the road towards true object-orientedness is long, and the system suffers in some manner from the current implementation. An "object" is given hereunder, and the link property appears including pointers to the connected objects:

```
(PLIST 'slope '(title   "The slope is "
                quest   "Is the slope ? "
                type    (code 1 2 3 4 5)
                1       "flat roof"
                2       "1%"
                3       "3%"
                4       "5%"
                5       "more"
                order   ("flat roof" "1%" "3%" "5%" "more")
                asked   ()
                to-be-checked  t
                link    (covering
                         upstands-height
                         waterproofing-composition)))
```

Some properties are used to store useful data for the interface management, such as "title" enabling to produce intelligible sentence frames filled with the value of the referred entity (to give an understandable insight to the factbase or to ease the production of readable reports), "quest" is a string used to ask a question to the user, to get the entity's value during reasoning, the "type" can be *entity* leading to booleen choices, *value* enabling numerical values such as integers or reals to be stored within the property , *interval* leading to express constraints on the acceptable domain of the slot, *code* or *constrained-code* for which a set of possible values is computed and prompted thanks to a graphical device offering a selection among possible values with checkboxes, the "help" slot is a text of aid, and link enables the system to keep trace of structured representations as many of Noe's entities are inherently hierarchically organized (Fig. 3), permitting coherency checking.

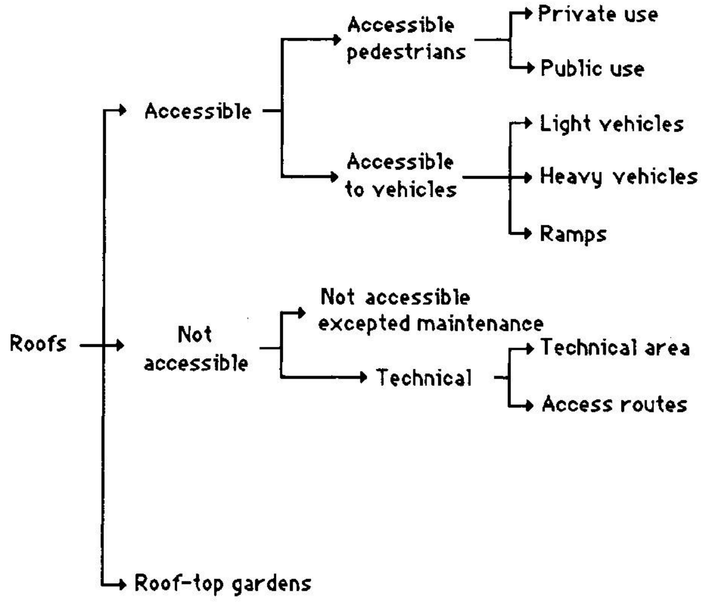

Fig. 3: Roof classification according to intended use.

3.3.2 Rules

Rules obey propositional logic, and enable the user to check entities slots' values, evaluating the Lisp code corresponding to the premises, and to modify the database in the same way by the triggering of the code attached to the actions. They offer basic functions, and do not require further explanations. An example is given bellow (as it appears when listed by the system):

```
IF    reverse-insulation = true
  and roof = roof-top-garden
  and ask the value of protection
  and protection <> foreseen

THEN      Modify : protection = foreseen
  and Modify : protection-type = Applied
  and Modify : applied-protection-type = draining-layer
```

The original Lisp form is the following:

```
( ( (test 'reverse-insulation ':= "true")
    (test 'roof ':= "roof-top-garden")
    (ask  'protection)
    (test 'protection ':<> "foreseen") )
    ;
  ( (remplace3 'bfl (list ':= "foreseen") 'protection)
    (remplace3 'bfl (list ':= "applied") 'type-protection)
    (remplace3 'bfl (list ':= "draining-layer")
                'applied-protection-type) )
  404)
```

This Lisp low level representation induces some limitations, but they were not problematic within the scope of a prototype, more especially as the software had to run on machines with limited resources. Moreover it gives the full flavor of Lisp as any kind of Lisp call can be merged within the rules to implement specific semantic purposes. Rule bases are just a superset, for which rules of the same topic are grouped within the same higher level entity.

3.3.3. Facts

A fact is a symbol to which we attached a list of properties with the following form, using the same mechanism as previously described:
((operator-1 value-1) (operator-2 value-2) ... (operator-n value-n))
and a factbase is a list (used as P-list to be coherent with the rest of the system), where two sorts of elementary data are stored , the one that was asked of the user and the one deduced by the expert system. So as to keep track of the modifications endured by the fact base, a global variable is used as a pointer to a structure enabling the transformations to be recorded.

3.4. Main functions

Main functions belong to two separate kinds, aiming either to address entities within the premises (ask the value, test the value of an entity, is-it-known ? or unknown ?), or to alter them by actions (add a new fact, suppress some value, substitute some value).

3.4.1 Functions to address entities

- (ASK <entity>): The ASK function questions the user about an entity's value, and stores the given result as a fact within the fact base. If ASK is sollicited with an argument already being filled with a value, this one is automatically returned without disturbing the user.

- (TEST <entity> <operator> <value>): This function enables the value of any entity to be tested within the fact base, and returns t or nil depending whether the predicate is verified or not. Example:

```
(TEST 'day ':<> "Monday")
```

- (KNOWN <entity>) and (UNKNOWN <entity>): These functions enable the user to determine if an entity is known or unknown within the fact base, i.e. if a value has been attached to it.

3.4.2 Functions to alter entities

- (PUT3 <fact base> <operator value> <entity>): This primitive enables a new fact to be added to the factbase. If no value was previously attached to the entity, this one is inserted, otherwise a new cons made of (operator value) is pushed inside the existing stack. Example:

```
(PUT3 'bfl (LIST ':= "Dimanche") 'Jour)
```

- (REM3 <entity>): Allows the suppression of the stack of values labelling an entity stored in the fact base. The consequent nodes are not affected by such a removal.

- (REMPLACE3 <fact base> <operator value> <entity>): This primitive is used to substitute a new fact to a list of value labelling an entity, using in fact (REM3 <entity>) then (PUT3 <fact base> <operator value> <entity>). Example :

```
(PUT3 'bfl (LIST ':= "Lundi") 'Jour)
```

Thanks to this small set of primitives, and to application dependent functions, it is possible to express nearly watherver the programer whishes for the kind of requirements encountered.

3.5 System Interface

The aim we had was to take advantage of the powerful graphical possibilities of the target machine to develop a very friendly interface, either based on the Macintosh dialogs or on resources. A Noé session relies on the interaction with graphical objects enabling the user either to get a booleen answer to an accurate question, to acquire text from line editors, to give an alert thanks to a message to be printed (Fig. 4), or to build complex pictures offering a set of possible selections thanks to checkboxes associated to icons for example as on (Fig. 5).

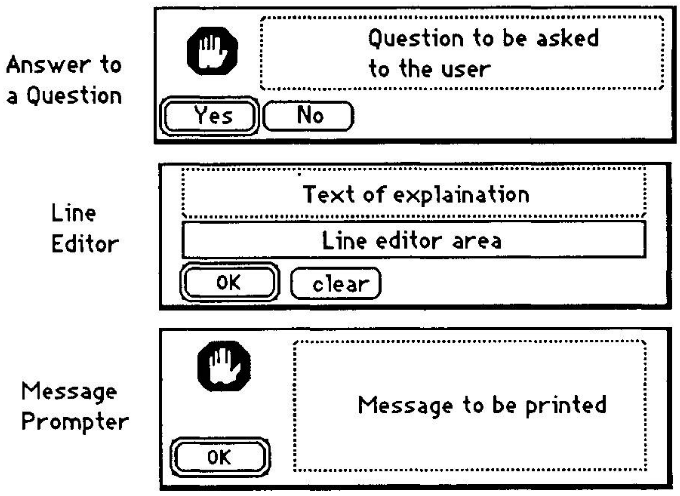

Fig 4: Some graphical objects used to manage user interaction.

Hereunder, Fig. 5 is an example of such concepts as it enables to select the type of the loadbearing slab structure, in an easier way than a textual description:

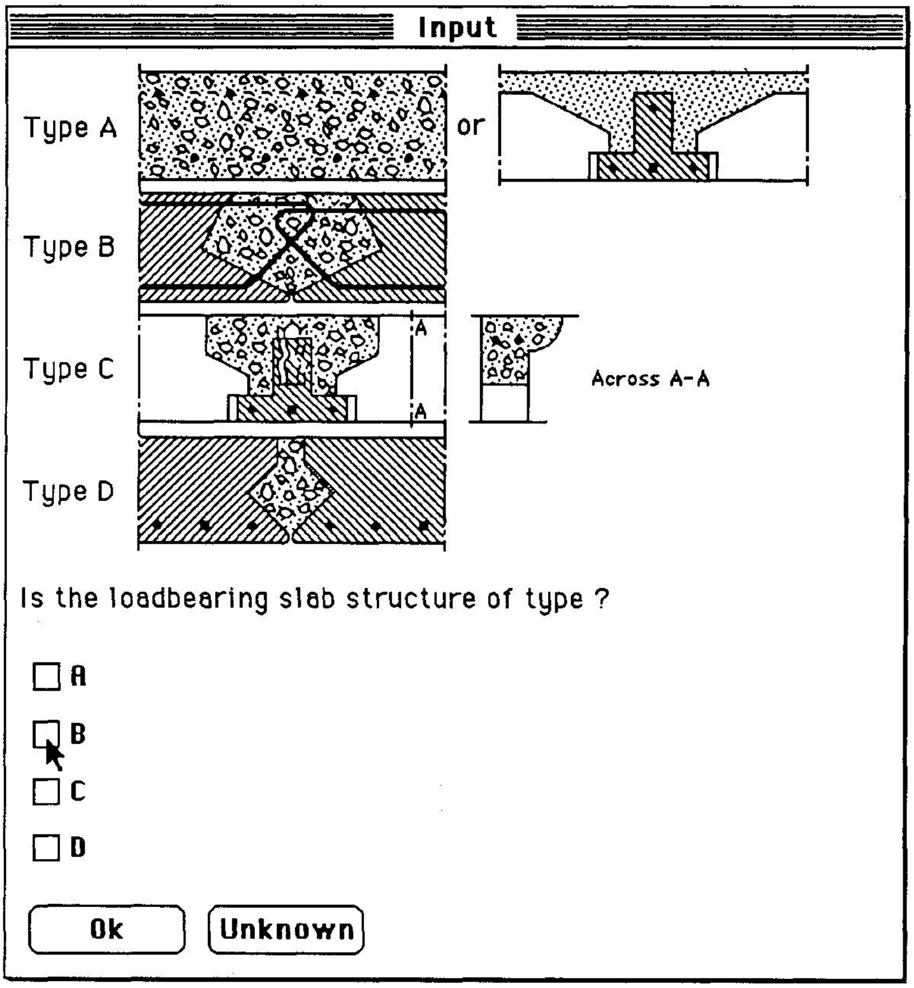

Fig. 5: Complex graphical objects enabling straightforward intercation.

The corresponding textual description could be:
- Type A: Loadbearing members of which at least the uppert part of the supporting section is constructed of reinforced concrete cast-in-situ continuously over the entire surface;
- Type B: Loadbearing members consisting of joined prefabricated reinforced or prestressed concrete members made rigid by reinforcement embedded in cast-in-situ connecting concrete;
- Type C: Loadbearing members consisting of joined prefabricated members of different materials made rigid by cast-in-situ blocks of concrete and/or transverse ties of reinforced concrete;
- Type D: Loadbearing members constructed using joined prefabricated reinforced concrete or prestressed concrete members made rigid by unreinforced concrete connections.

These data can be useful as the meaning of the results we are going to present now (section 4) are very dependent from the type of the loadbearing slabs encountered.

4. RESULTS

4.1 Control results during the design phase

When we presented the general organisation of the system (Fig 1), and made the task analysis (§2.1), we asserted that three kinds of data were produced to conform to the human controller step. Moreover some rules aim to schedule verifications and activate computing instead of the controller, such as the computing of the thermal insulation resulting from the composition and the thickness of the insulating material. All these data make up the preliminary report, corresponding to the pre-project analysis. We give an example of a design level rule:

```
IF     slope = no
  and ask the value of upstand
  and upstand = foreseen
  and ask the value of upstand-height
  and upstand-height < 15

THEN     add : prescription "The height of upstand covered with
waterproofing must be such that the minimum height of the waterproof
skirting at any point be at least 15 cm when the roof is flat"
         and Modify : upstand-height = 15
```

Then the conclusions of the system are available:
Prescriptions:
Heavy-duty protection is obligatory for multilayer coverings,
There is to be an arrangement above the waterproof skirting to divert the water running off members of the main structure whixh are above it so as to prevent water from getting behind the waterproof covering,
If there is only one rainwater downpipe, an owerflow device must be foreseen,
Recommendations:
It is recommended to have no slope within eaves,
Eaves should be avoided,
Advice:
It is better to foresee a hard protection for skirtings in case of hard protection of the main roof.

4.2 Control results during the execution phase

We remember the reader, that the execution phase (from the controller viewpoint), takes place just before that the effective installation of the waterproofing be done. We encounter the same sort of rules but they lead to more accurate controls. The prescriptions produced at the end of this phase are really more precise like the following:
Prescriptions:
The skirting is to consist of: a cold priming coat, a layer of hot-applied coating to the right of the reinforcing angle piece, a reinforcing angle piece 0.20 m broad with equal limbs, of type 40 reinforced bitumen, cloth reinforcement, welded or stuck, a layer of hot applied coating, a reinforced bitumen type 40 TV with incorporated metal foil protection, with a toe of 0.15 m on horizontal part, welded,
The bridging of the joints in case of loadbearing slab of type D must be foreseen during the installation of the vapour barrier, and be at least of 0.20 m large.
The vapour barrier system should be made of a layer of cold priming coat, a layer of hot-applied coating, a bituminous felt of type 36 S (VV-HR), ended with a layer of hot-applied coating,
Any point on a flat roof must be within 30 m of the collecting device (eave or trough gutter) or rainwater outlet. The maximum distance between two downpipes from an eave of trough gutter is 30m).,
etc...

4.2 Control results during the installation phase

The aim of this step is to produce the final report. In order that no remaining data should be left with an unknown status, checking forms are produced by the system, and enable the operator to accomplish on site checking of the corresponding characteristics. First of all, a summary of the overall properties of the project is given. It could appear as the following report:

The roof is not accessible,
There is no slope,
The waterproof covering is a multilayer,
There are loadbearing insulating board supports,

A vapour barrier is foreseen,
A protection is foreseen,
The insulation is 12 cm thick,
Expansion joints are not foreseen,

etc...

Then verifications are suggested by the software and lead to on site checking. This phase can be repeated several times and indications have the following form:

Verifications:

Rainwater outlets are made up of two parts: the flashing and the spigot, which are assembled by welding or by any other method providing a permanent watertight joint. It should be verified that the distance between the external edge of the outlet hole and the outside edge of the plate is not less than 0.12 meter.,

etc...

5. CONCLUSIONS

Noé is an operational prototype, reproducing the step followed by a technical controller in the area of waterproofing work on flat roofs. The system's behaviour is mapped on the observed state of the art habits of human experts, and implements a succession of control procedures, being more and more refined, so as to finally produce an end of phase report when on-site checkings are successful. The software takes advantage of the powerful capabilities of the graphical toolbox of the Macintosh, so as to offer a high level interface, enabling a wide public to benefit from it. Specific functions had to be defined to handle the temporal consequences of modifications to the initial design, and the system is able to deal will real evolving projects. Nevertheless, improvements will be made in many respects, to provide self-explanation possibilities, to handle the regulation documents accurately, and to virtualize many concepts, allowing a machine independent system to be obtained.

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Expert System for Repair of Concrete Structures

Système expert pour la reparation des structures en béton

Expertensystem zur Instandsetzung von Betonbauteilen

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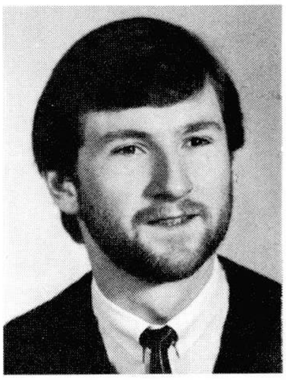

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SUMMARY
An expert system for the maintenance and repair of concrete structures based on an ES-Shell is discussed. The expert system is intended to help the civil engineer to investigate the condition of a building. The causes of damage will be revealed and analyzed in a dialogue between user and computer. After finding out the causes of deterioration different repair proposals are given.

RESUME
Un système expert, basé sur un Shell ES pour l'entretien et la réparation des structures en béton est présenté. Le système doit aider l'ingénieur qui juge l'état des bâtiments et des ouvrages d'art. Les causes des dommages sont analysées et expliquées pendant un dialogue entre l'utilisateur et l'ordinateur. Après la définition des causes des dommages, différentes possibilités de réparation sont proposées.

ZUSAMMENFASSUNG
Ein Expertensystem für die Unterhaltung und Instandsetzung von Betonbauteilen wird vorgestellt, das auf einer ES-Shell aufgebaut ist. Das Expertensystem soll Ingenieure bei der Beurteilung des Zustandes von Bauwerken unterstützen. Die Ursachen der Schäden werden in einem Dialog zwischen Benutzer und Computer analysiert und erläutert. Nachdem die Schadensursachen ermittelt sind, werden verschiedene Reparaturmöglichkeiten vorgeschlagen.

1. INTRODUCTION

The repair of damaged concrete structures has become more expensive in the last years. It was found that, in many cases, the engineers' training and experience was not enough to decide on the right repair works. There are exact scientific models for structural design but not for concrete repair. Here, the knowledge is dispersed in different papers, guide lines, regulations, and producers' instructions. There is a need to analyze the knowledge and experience and to prepare it for easier use on a higher level.

An expert system can save the knowledge of experienced engineers and combine the complex and heuristic relations. In our institute a prototype of an expert system is being developed, which is intended to support engineers in judging the damaged structures and to give repair proposals. The system includes the new regulations by the German Association for Concrete and Reinforced Concrete (Deutscher Ausschuß für Stahlbeton) entitled "Protection and Repair of Concrete Structures" [3] as far as they are released.

2. EXPERT SYSTEMS

2.1 Definition

Artificial intelligence is a field in computer research, where human performance is imitated with computers. To solve problems, intelligence is required. The human intelligence is devided into different abilities, such as understanding of the spoken language, parallel thinking, i.e. searching for a solution to a problem in different ways at the same time, or learning of new facts. One group, which is already well tested in practice, deals with knowledge-based expert systems.

Edward Feigenbaum, Stanford University, one of the prominent scientists in artificial intelligence, gave the following definition of expert systems:

> An intelligent computer program that uses knowledge and inference procedure to solve problems that are difficult enough to require significant human expertise for their solution [2].

2.2 Differences with conventional programming techniques

Conventional computer languages are e.g. FORTRAN, PASCAL, or BASIC. These languages are used for data processing of large data and for mathematical computations applying algorithms in always the same way. The main differences between conventional and symbolic programming languages are given in Table 1.

Table 1: Main differences between conventional and symbolic programs

Conventional Programs	**Symbolic Programs**
Algorithms	Heuristics
Numerical adresses in data base	Symbolic structured knowledge base
Orientation to numerical processing	Orientation to symbolical processing
Sequential, batch processing	Interactive processing
No explanations possible during program-run	Explanations during program-run easily

Most knowledge-based expert systems are written in symbolic or declarative languages, e.g. LISP or PROLOG. The systems are extensive interactive and the user can stop the consultation in order to ask why the system puts forward a particular question or how this resolution is done. Other advantages are the easy way of modifying the knowledge base, which is different from the inference mechanisms. Fig. 1 shows the tpyical setup of an expert system.

2.3 Applications of expert systems

Problems, which can be solved by experience on heuristics only, are suitable for use in expert systems. Some existing applications are listed in the following:

Diagnosis

The program must find the failure function of a system by analyzing the symptoms. These failure functions can be a disease of the human organism (e.g. MYCIN), mistakes in mechanical equipment, or damages to building structures (e.g. REPCON, discussed in chapter 4).

Planning

Planning tasks are e.g. to find the best hardware configuration for special applications, to make a financial decision, or to design buildings [1].

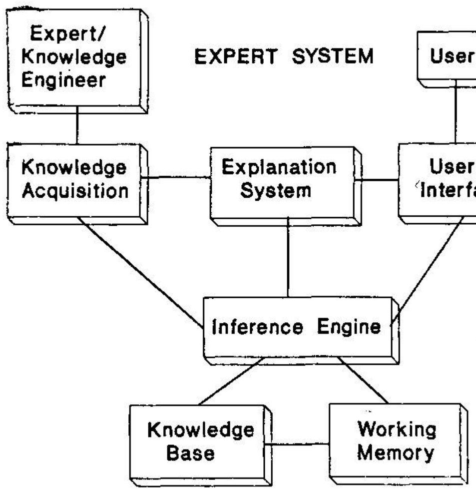

Figure 1: Typical setup of an expert system

Evaluation

Geological data must be evaluated for finding mineral resources (e.g. PROSPECTOR).

Supervision

Complex system functions must be supervised and the decisions must be made nearly in real time. Applications are used for intensive medical or mechanical equipment or ready-mixed concrete [7].

2.4 Expert-system shells

Expert-system shell means an expert system with an empty knowledge base. In our project, we use a shell named "Personal Consultant Plus" from Texas Instruments. The shell is written in the LISP-Dialect SCHEME. This shell was developed from EMYCIN (Essential MYCIN), i.e. the concepts of MYCIN, also certainty factors can be used. Frame-structure, Meta-Rules, and grafic facilities were added.

There are external accesses to MS-DOS, e.g. to start a program written in BASIC or PASCAL, or to send and read data from DOS-files. Hardware requirement is an IBM-compatible Personal Computer with a minimum of 640 kB RAM with grafic mode EGA.

3. CERTAINTY FACTORS

3.1 Purpose

A certainty factor (CF) is a numerical value that indicates a measure of confidence in the value of a parameter. Certainty factors in a knowledge base consider the real experience that facts and opinions are not always known with absolute certainty.

An expert system may encounter two kinds of uncertainty:

- The facts and relationships of the problem area encompass uncertainty. Frequently, the expert has to make statements like this: "If these conditions are met, this outcome occurs almost always. Once in a while, however, a different outcome may occur."
- The user may feel a degree of doubt in responding to a prompt. "I don't exactly know if there was a certain event in the life of the structure (for instance elevated temperatures), but I suppose there was."

3.2 Combining Certainty Factors

An example will show how the expert system deals with certainty factors. Supposing you find cracks in concrete structures and you have to find out the cause. The following two rules are part of the knowledge base:

Rule 1:
If: DAMAGE-MARK = CRACKS and
CRACK-TYPE = RANDOM-PATTERN and
ELEMENT = MASS-CONCRETE and
ENVIRONMENTAL-CONDITIONS-DURING-HYDRATION = LOW-TEMPERATURE

Then: CAUSE = LOSS-OF-HEAT-OF-HYDRATION CF 50

Rule 2:
If: START-OF-DAMAGE = FIRST-DAYS-AFTER-PLACEMENT and
CEMENT-TYPE is not LOW-HEAT-CEMENT

Then: CAUSE = LOSS-OF-HEAT-OF-HYDRATION CF 90

The consultation could run in this way. After having answered that you found RANDOM-PATTERN and the element was MASS-CONCRETE, the system prompts this:

"Describe the environmental conditions and indicate your degree of certainty". You may answer: "COLD with 70 % certainty." The conditions of the first rules IF-statement are met and the system combines the appropriate certainty factor, including the certainty factor you assigned in the rules THEN-statement.

CAUSE = LOSS-OF-HEAT-OF-HYDRATION CF 35 (70 per cent of 50)

The system considers other causes, because the conclusion is not true for 100 %. It will ask for the values of the parameters of rule two. Suppose you know that the damage started during the first days after placement. You don't exactly know the type of cement which was used, but you suppose that not a cement with low heat of hydration was used. You answer with a degree of certainty of 50 %. The expert system uses the following equations to combine the degrees of certainty.

$$CF(rule) = \frac{CF\ of\ IF - statement \cdot CF\ of\ the\ conclusion\ function + 50}{100} \quad (1)$$

$$CF = CF(previous) + \frac{CF\ (rule) \cdot (100 - CF(previous)) + 50}{100} \quad (2)$$

CF(previous) is the certainty factor with the parameters value before the expert system carries out the action of the THEN-statement of the next rule. Note that the last 50 in the numerator of the equations is included for rounding and only the integer part is used.

Example:
Using equation (1):

$$CF(Rule\ 1) = \frac{70 \cdot 50 + 50}{100} = 35,5 \Longrightarrow CF35$$
$$CF(Rule\ 2) = \frac{50 \cdot 90 + 50}{100} = 45,5 \Longrightarrow CF45$$

Using equation (2):

$$CF = 35 + \frac{45 \cdot (100 - 35) + 50}{100}$$

$$35 + 29 = 64 \Longrightarrow CF64$$

The cause of the cracks still is LOSS-OF-HEAT-OF-HYDRATION, but the additional evidence increased the certainty factor to 64.

4. "REPCON" AN EXPERT SYSTEM FOR CONCRETE REPAIR

First, the structure and the structural parts of a building have to be specified. Some important information may help to find the causes of damage, e.g. structures in sea water or near streets, should be tested for chloride content.

The causes of damage will be revealed and analyzed in a dialog between user and expert system. Different types of damages are presented in knowledge base rules, e.g. corrosion due to carbonization, chlorides, or chemical causes. The use of grafics with typical pictures of the damages supports the discussion and the analysis. Fig. 2 shows the structure of the expert system "REPCON".

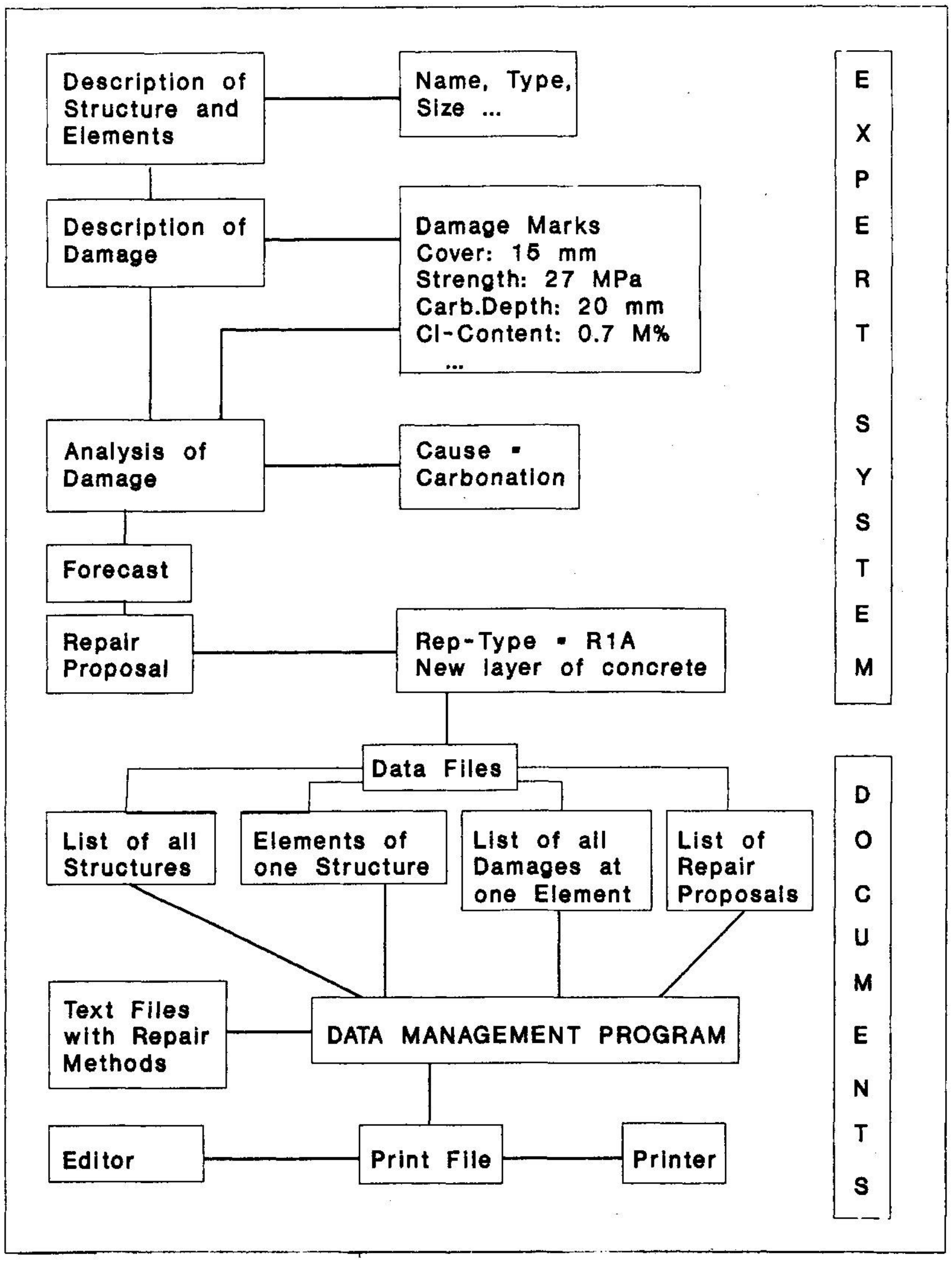

Figure 2: Structure of the expert system REPCON (with example)

All data necessary for the description of the structure and the repair will be saved in an extra data base for future consultations with respect to the same structure. After having found the causes for deterioration, different repair proposals will be given. The proposals comprise information about the repair method, repair materials, as well as quality of the repair work with respect to durability and esthetics and repairing expenses. At the end of the consultation, the user can receive a list of the input data and the conclusions drawn by the system.

5. CONCLUSIONS

An expert system for the maintenance and repair of concrete structures is being built on the basis of an ES-Shell. The expert system is intended to help the civil engineer to find out the condition of a building and to give repair proposals.

The prototype program REPCON shows that the use of an expert system is a possible way to save the knowledge, which is dispersed in numerous papers and in a few human experts. This kind of computer programs can help to make the right decision. They cannot and should not replace human experts.

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An Expert System for Damage Assessment of Bridge Structures using Fuzzy Production Rules

Système expert pour l'évaluation des dommages des ponts en utilisant les règles de la logique floues

Expertensystem zur Berechnung von Schäden bei Brückenstrukturen unter Verwendung von Fuzzy-Produktionsregeln

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SUMMARY

This paper attempts to develop an expert system for assessing damage states of bridge structures, where the focus is on the reinforced concrete bridge deck, because its failure has been occasionally reported. Similar to the usual expert systems, this system consists of interpreter, rule-base and working memory. Using this system, it is possible to deal with various kinds of uncertainties and ambiguities involved inherently in the data, rules and inference process in a unified and simple manner. An illustrative example is presented to demonstrate the applicability of the system developed herein.

RESUME

Cet article décrit le développement d'un système expert d'évaluation de l'état des dommages des structures de ponts. L'attention s'est portée sur le tableau en béton armé du pont, car des défauts ont été occasionnellement reportés dans cette partie de l'ouvrage. Comme pour les systèmes experts ordinaires, ce système comprend un interpréteur, une base de données et une mémoire active. Avec ce système, il est possible de traiter un nombre varié de cas incertains et d'ambiguités inhérentés aux données, aux règles et aux procédés de déduction d'une manière unique et simple. Un exemple illustre l'utilisation du système développé dans cet article.

ZUSAMMENFASSUNG

In dieser Arbeit wurde versucht, ein Expertensystem zur Schadenberechnung von Brückenstrukturen zu entwicheln, wobei der Schwerpunkt auf Stahlbeton-Fahrbahnen liegt, weil für diese Bauart öfters über Einsturzprobleme berichtet wurde. Wie bei den üblichen Expertensystemen, besteht das neuentwickelte System aus Interpreter, Rule-Base und Working Memory. Dieses System erlaubt deshalb die einfache und einheitliche Behandlung verschiedener Ungewissheiten, die in den Daten, Rules und Inference-Prozessen vorhanden sind. Ein erläuterndes Beispiel soll die Anwendbarkeit des neuen Systems klar machen.

1. INTRODUCTION

Expert Systems are relatively new and can be attractive to structural engineers. An expert system is a useful tool for solving ill-defined problems in which intuition and experience are necessary ingredients[1]. The problem of damage assessment is a typical one of ill-defined problems in the field of structural engineering[2].

In order to establish an efficient repair and maintenance program, it is important to evaluate the damage states of existing structures[4]. However, the damage assessment of structures is not easy due to the lack of available information and the complex mechanism of structural deterioration. Therefore, the daily maintenance has been so far carried out on the basis of intuition and engineering judgment of experienced engineers.

In this paper, we attempt to develop an expert system for assessing the damage states of bridge structures. As the first stage, we pay attention to the damage assessment of reinforced concrete (RC) bridge deck. This is why many failures have occurred in the RC bridge deck which directly resists the applied loads[3].

A number of problems arise when an expert system is built for the practical use. How to treat uncertainty and ambiguity is one of problems which we face occasionally. In this paper, those uncertainties or ambiguities are handled using the theory of fuzzy sets[7]. Namely, the present expert system has such a remarkable feature that it includes a fuzzy operating system which can treat fuzzy sets in the process of data handling, rule representation and inference procedure. Using this system, it is possible to deal with various kinds of uncertainties and ambiguities involved inherently in the data, rules and inference process in a unified and simple manner. Similar to the usual expert systems[5], the damage assessment system consists of interpreter, rule-base and working memory. An illustrative example is presented to demonstrate the applicability of the system developed herein.

2. FUZZY PRODUCTION SYSTEM

In order to derive a meaningful conclusion from imprecise and ambiguous information and knowledge, a special inference procedure is necessary. In this paper, a fuzzy reasoning method[8] is employed for this purpose. The outline of fuzzy reasoning and its role in the production system are described as follows.

In usual, human beings recognize and memorize knowledge and experience by such linguistic expressions as "A red apple is rape" or "A tall man has long legs". These expressions can be represented in terms of "If••••, then••••• " phrases; "If an apple is red, then it is rape" and "If a man is tall, then he has long legs". However, the adjectives of red, tall and long have ambiguities apparently. It may be impossible to treat those ambiguities associated with the use of natural language in terms of probabilistic methods or certainty factors. In other words, those methods can not derive a conclusion for such information as that an apple is a little bit red or a man is very tall. Fuzzy reasoning method was proposed to deal with this kind of information and therefore it is called as "approximate reasoning"[8].

Based on fuzzy reasoning, a production rule is expressed as

$$\text{If } X \text{ is } \tilde{A}, \text{ then } Y \text{ is } \tilde{B}. \qquad (1)$$

where the attributes of X and Y are defined by fuzzy sets and the symbol~

denotes a fuzzy quantity. Even if we obtain the input $\tilde{A}'$ which is somewhat different from $\tilde{A}$, we can derive a meaningful conclusion $\tilde{B}'$ using Eq. 1. Moreover, it is possible to give truth values to input data, rules and conclusions. Here, the truth values are also defined by fuzzy sets. For example, "very true" and "true" are specified as

$$\text{"very-true"} = \{0.3/0.8,\ 0.8/0.9,\ 1/1\} \tag{2}$$

$$\text{"true"} = \{0.2/0.6,\ 0.7/0.7,\ 1/0.8,\ 0.8/0.9\} \tag{3}$$

where the symbol / is a separator and the former part means the membership grade and the latter means the truth value which is defined in the range of [0,1]. The value 0 denotes the absolute false and the value 1 denotes the absolute true.

According to the expression of fuzzy reasoning, the input data and rules are written as follows:

```
(database   very-true/(temperature more-or-less-high)
                 true/(throat-pain slightly-small)
                 true/(headache more-or-less-strong)          (4)

(rules diagnosis
   rule-1
      if (temperature high)
         (throat-pain moderate)
      then (deposit (disease cold)
           (*cf times very-true =match)
   rule-2
      if (temperature high)
         (headache very strong)
      then (deposit (disease influenza)
           (*cf times =match)                                 (5)
```

where "database" is a Lisp function to register the input data and "diagnosis" is the name of rule-base and both rule-1 and rule-2 are the names of rules. The symbol = denotes a variable, and =match stores the value of matching degree between the input data and the antecedent of the firing rules. The truth value of the conclusion is calculated through a fuzzy operation between =match and the truth value of the corresponding rule. To select the calculating operator, the Lisp function *cf is employed. The phrase (*cf times =match) means that the calculating operation is the multiplication. The symbol * is used to represent a Lisp function. The detail of the matching process is referred to Ref. [6].

3. ARCHITECTURE OF THE PRESENT SYSTEM

The present expert system consists of the IO system(input and output system), interpreter(inference engine), rule-base, working memory and fuzzy operating system, as shown in Fig. 1. The input data are stored in the working memory through the IO system. The IO system is developed to make the load for data input lighter. When the amount of input data is large, they are categorized and stored in different regions of working memory. The division of working memory is useful for shortening the implementation time. The interpreter works to select adequate rules from the rule-base and implement the reasoning process. The fuzzy operating system is used when fuzzy sets appear in the implementation of the reasoning. All the above systems are written in Lisp. The present system is developed on a 32 bit engineering workstation. By using the

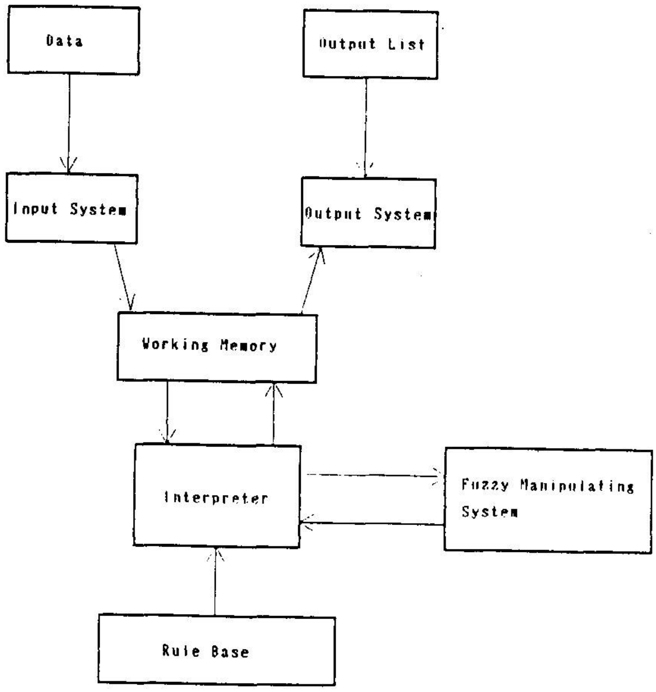

Fig. 1 Architecture of system

engineering workstation as the hardware, we can take such advantages as the easiness of transfer and the improvement of computer environment.

4. DAMAGE ASSESSMENT SYSTEM FOR REINFORCED CONCRETE DECK OF BRIDGE STRUCTURE

This paper attempts to develop an experts system for assessing the damage states of bridge structures, where the focus is put on reinforced concrete (RC) bridge deck, because its failures have been occasionally reported. The system has the following characteristics:

1) Lots of valuable expertise regarding the damage cause and damage propagation of reinforced concrete bridge deck can be acquired through a considerable number of interviews for experts of maintenance work.
2) It is possible to deal with the ambiguity and uncertainty involved in data and knowledge by introducing the fuzzy reasoning.
3) To assess the structural damage properly, the remaining life of RC bridge deck is employed as a final form of result, which is estimated on the basis of three measures; damage cause, damage degree and damage propagation speed.

In this system, the past records and inspection results are used as the input data. When the inspection results regarding cracks are firstly input into the system, the matching processes for rules concerning their damage cause, damage degree and damage propagation speed are implemented to provide a solution for the remaining life. This inference procedure is performed as shown in Fig. 2. At first, based on the inspection results, the damage is classified into cracks, damage of pavement, damage of reinforcing steel, damage of concrete, and structural damage. Followingly, using the design and environmental conditions as well as the inspection data, possible damage causes are estimated. Table 1 presents representative damage causes which are categorized by loading condition, design and structural condition, construction condition and other

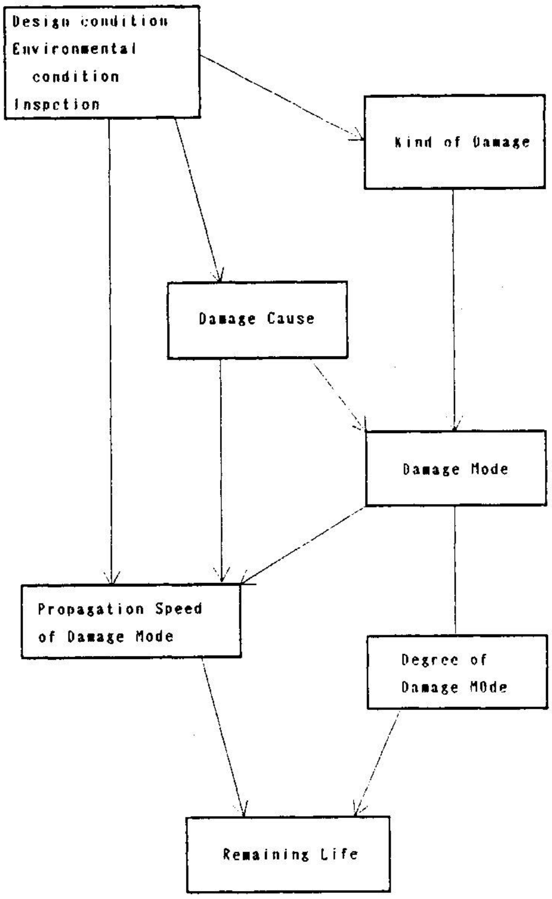

Fig. 2 Inference process

Table 1 Representative damage causes

Load	Extreme wheel load Impact effect inadequacy of girder arrangement
Design and structural factor	Short of deck depth Lack of main steel bar Lack of distribution bar Inadequacy of distributed cross beams Additional moment due to differential settlement
Construction condition	Poor quality of cement Poor compaction Inadequate curing of construction joint Lack of covering
Other Factors	Salt Poor drainage Movement of substructure

conditions. In general, multiple damage causes are estimated, to which "damage mode" is taken into consideration. The damage mode means a group of several damages resulting from the same cause. Identifying a damage mode, damage degrees are evaluated for every kinds of damage. Based on their evaluations, a damage degree to the damage mode is obtained. Similar to the process, the damage propagation speed is assessed by considering the damage causes estimated. Finally, the remaining life is estimated using the construction year and the results obtained above.

It is assumed that the relation between the construction year and the damage degree for intact structures can be expressed by S-0 curve in Fig. 3. Moreover, S-1 to S-5 curves are prepared for structures with very severe damage, severe damage, moderate damage, slight damage and very slight damage, respectively. For example, consider a structure built 20 years ago, whose damage degree is slight and damage propagation speed is slow. The present damage state of this structure is located at a point P in Fig. 4. Since the propagation speed "small" is less than the propagation speed after 30 years of the curve S-0, the propagation speed is replaced by the S-3 curve in the region larger than 30 years. Hence, the damage proceeds according to the solid line P-R-Q. Then, the remaining life is obtained as the subtraction between the abscissas of Q and P.

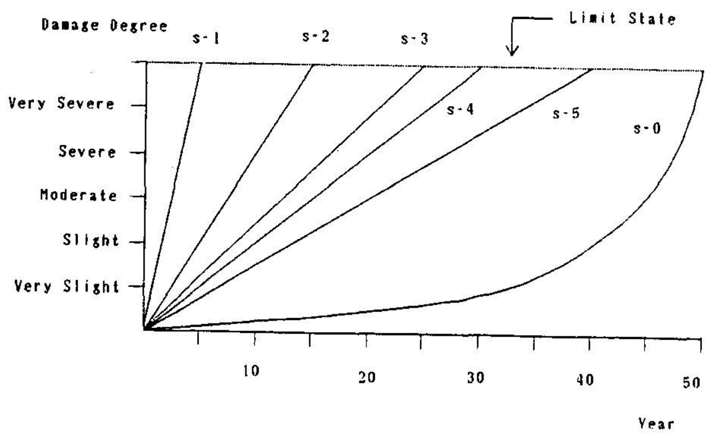

Fig. 3 Relation between construction year and damage state

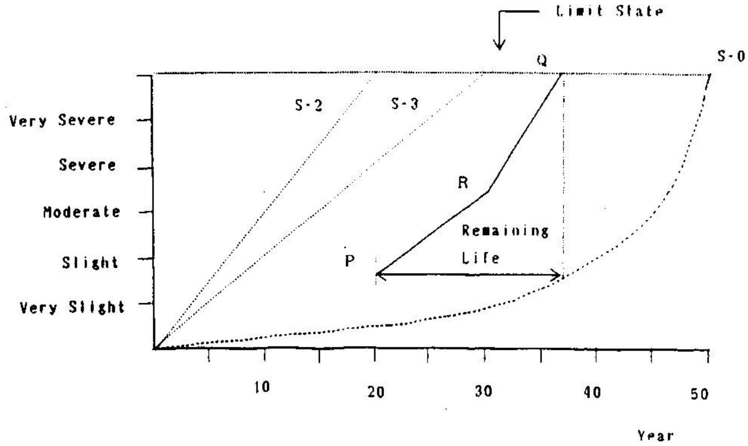

Fig. 4 Estimated remaining life

5. APPLICATION EXAMPLE

To illustrate the applicability of the present fuzzy expert system, consider a 3-spanned cantilever plate girder bridge which was built in 1938. Table 2 presents the design and environmental conditions of this bridge. The damage assessment is performed panel by panel. A panel is a region surrounded by main girders and cross beams. Employing a panel called P-1 as an example, the inference process is described in the following.

Table 2 Design and environmental conditions

Kind	Factor	State	Truth Value
Crack	Direction	Direction to bridge width	FL
	Location	Center of deck span	FL
		Haunch	M
	Density	1.72 m/mm^2	1
	Between distance	Large	FL
	Width	Medium	FL
Concrete	Free lime	Medium	FL

Table 3 Inspection results

Kind	Factor	Data	Truth value
Design	Structural type	3-spanned cantilever girder bridge(straight)	1
	Design specificastion	Before 1967	1
	Construction year	Old	Large
Condition	Deck width	20 cm	1
	Bridge length	69.00 m	1
	Bridge width	12.95 m	1
	Lanes	3 lanes	1
	Footway	One-side	1
	Road rank	Main road	1
Environment	Rate of heavy vehicle	Medium	FL
	Location of wheel load	Center of deck span	Large

Using the inspection results shown in Table 3 as well as the design and environmental conditions, several damage causes were estimated, as shown in Table 4. Fig. 5 shows the rules which were used to estimate the damage causes (1). From these damage causes, a damage mode is determined. Followingly, the damage propagation speed is estimated using the damage causes and the environmental conditions. These results are summarized in Table 5. Based on these inference results, the remaining life of the panel is obtained as shown in Table 6. Considering that this bridge exists in the road with large traffic volume and the adopted design code is an old version published in 1926, it is reasonable that the extreme wheel loads and the lack of distribution bars were chosen as damage causes for cracking. Moreover, the defect of surface drainage largely affects the estimation of remaining life, because the damage propagation speed of this damage cause is very quick.

```
(rule-1-1-2-2
 if  (crack configration width-direction)
     (crack location center-of-deck-span)
     (wheel-load location center-of-deck-span)
     (design-specification before-1967)
 then (deposit (damage-cause exteme-wheel-load)
     (*cf times very-true =match)))

(rule-1-3-4-5
 if  (crack configration width-direction)
     (crack location haunch)
     (design-specification before-1967)
 then (deposit (damage-cause exteme-wheel-load)
     (*cf times fairly-true =match)))

(rule-1-5-3-6
 if  (crack configration bridge-direction)
     (crack location center-of-deck-span)
     (design-specification before-1967)
     (wheel-load location center-of-deck-span)
 then (deposit (damage-cause exteme-wheel-load)
     (*cf times true =match)))
```

Fig. 5 Examples of rules for damage causes

Table 4 Estimated damage causes

	Damage cause	Truth value
Cause(1)	Extreme wheel load	Fairly Small
Cause(2)	Lack of distribution bars	Fairly Small
Cause(3)	Poor drainage	Fairly Small

Table 5 Inference results for damage propagation

Damage cause	Damage degree	Truth value	Damage propagation	Truth value
(1)	Medium	Small	Medium	Fairly Small
(2)	Medium	Small	Medium	Small
(3)	Large	Small	Fairly Large	Fairly Small

Table 6 Estimated remaining life

Damage cause	Remaining life	Truth value
Cause(1)	5 to 10 yrs.	Fairly Small
Cause(2)	5 to 10 yrs.	Small
Cause(3)	2 yrs.	Fairly Small

6. CONCLUSIONS

This paper attempted to develop a practical method of evaluating the damage states of bridge structure, that is important to establish an efficient repair and maintenance program. Considering the importance of the knowledge and intuition of experienced engineers in the daily maintenance work, a fuzzy expert system for the damage assessment of the concrete bridge deck was constructed, consisting of interpreter, rule-base and working memory. This system was written in Franz Lisp and implemented on a 32 bit engineering workstation.

The following conclusions were derived:

1) A large number of rules useful for the damage assessment could be acquired through an intensive interview with well-experienced engineers on repair and maintenance works. By introducing the fuzzy operating system into the expert system, it is possible to utilize the knowledge and rules which are expressed in terms of natural language. This enables us to acquire the expertise with ease.
2) Based on the fuzzy reasoning, it is possible to reduce the number of rules necessary for deriving a meaningful conclusion. The reduction is very useful for building a practical expert system.
3) Introducing the concept of damage mode, the reliability of the damage assessment can be increased. Furthermore, the remaining life is valuable to provide useful information to establish a future maintenance program.
4) Although any expert system including the expert systems developed herein is, even now, not completely practical, it may provide substantial assistance to more complicated or creative works which are usually not completely or well defined. In order to make the expert systems to be actually useful, some improvement is desirable on such issues as the knowledge acquisition, knowledge representation, treatment of ambiguity or uncertainty, and man-machine interface.

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Expert System for Maintenance and Rehabilitation of Concrete Bridges

Système expert pour la maintenance et la restauration de ponts en béton

Expertensystem für Unterhaltung und Sanierung von Betonbrücken

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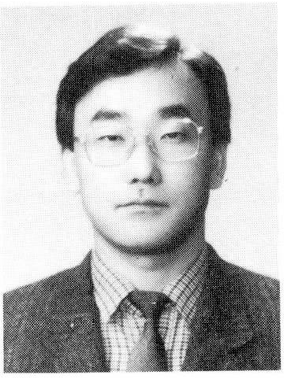

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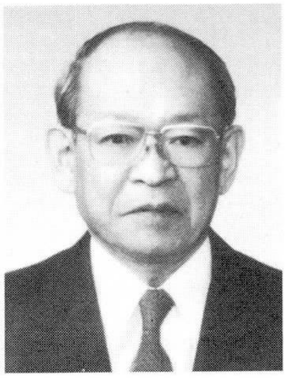

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SUMMARY
The present paper aims to introduce a newly developed expert system which is capable not only of various inferences and judgements for maintenance but also of output of consultation results on repair and rehabilitation techniques. Moreover, its application to some reinforced concrete T-beam bridges in service is also considered. For the construction of the knowledge base including the subjective information related to bridge rating, a concept of the basic probability according to the Dempster & Shafer's theory was adopted to deal with it. The final results produced by this system are considered to be represented by five elements expressed by linguistic expressions with the fuzziness value which is the degree of subjective uncertainty.

RESUME
Cet article décrit un système expert, de type base de connaissance, pour la détermination de l'aptitude à l'utilisation de ponts en béton. Le présent système applique les concepts des probabilités de base selon la théorie de Dempster et Shafer pour tenir compte des informations subjectives relatives à l'évaluation du pont. Les rèsultats finaux obtenus avec ca système sont considérés comme étant présentés avec cinq éléments exprimés par des expressions linguistiques avec une valeur vague qui est la degré d'incertitude subjective.

ZUSAMMENFASSUNG
Diese Abhandlung beschreibt ein wissensbasiertes Expertensystem für die Wartbarkeitsbewertung von Betonbrücken. Das vorliegende System verwendet die Konzepte der grundlegenden Wahrscheinlichkeit nach der Theorie von Dempster & Schäfer zur Handhabung der mit der Brückenbewertung zusammenhängenden Informationen. Für die durch dieses System erhaltenen Endergebnisse wird angenommen, dass sie mit fünf Elementen dargerstellt werden, die durch sprachliche Ausdrücke zusammen mit dem Verschwommenheitswert, dem Grad der subjektiven Ungewissheit, ausgedrückt werden.

1. INTRODUCTION

The necessity of developing a computer-aided bridge rating system has been pointed out for maintenance, diagnosis, repair and rehabilitation of existing bridges. There are multiple processes of damage with a number of damage factors in existing bridges in service. The major part of bridge rating which is the kernel of bridge maintenance system has been constructed based on the subjective judgment of experts in the related fields. By considering that there is a lack of experts in the increasing field of bridge maintenance and for the exact diagnosis of bridge conditions, the systematization of bridge rating including the subjective information of bridge engineers such as professional experience, knowledge on bridge rating, etc. has become an important problem.

In this paper, an expert system for serviceability rating of concrete bridges (Bridge Rating Expert System) is developed based on a combination of several components which are the knowledge base including the subjective information related to the rating, the inference engine, the data reference module, the calculation module, the explanation module, the knowledge acquisition module and the I/O module. The computer system and main language which is used in the expert system are the PC-9801VX41 personal computer made by NEC Corporation, Japan and PROLOG and C languages, respectively.

For the construction of the knowledge base including the subjective information related to the rating, it is an unavoidable problem in dealing with subjective informations which cannot be allotted binary codes such as true or false. As a remedy to this problem, a concept of the basic probability according to the Dempster & Shafer's theory is introduced in the present system. The upper probabilities in the Dempster & Shafer's theory to introduce experiences and knowledge accumulated into the knowledge base are obtained through questionnaires sent out to bridge experts.

The results of the rating at the final stage produced by this system are considered to be represented by five elements expressed by the linguistic expressions "safe" "slightly safe" "moderate" "slightly danger" "danger" with the fuzziness value which is the degree of subjective uncertainty.

A few concrete bridges on which field data have been collected are analyzed to demonstrate the applicability of this expert system. Through the application to the deteriorated reinforced concrete bridge girders and slabs, reasonable results are obtained by inference with the expert system.

2. SYSTEM DESCRIPTION

The Bridge Rating Expert System is a newly developed microcomputer knowledge-based system which is capable of various inference and judgment. The general feature of this expert system is illustrated in Fig.1. As shown in Fig.1, the expert system consists of seven main components: the knowledge base system, the inference engine, the data reference module, the calculation module, the explanation module, the knowledge acquisition module and the I/O module.

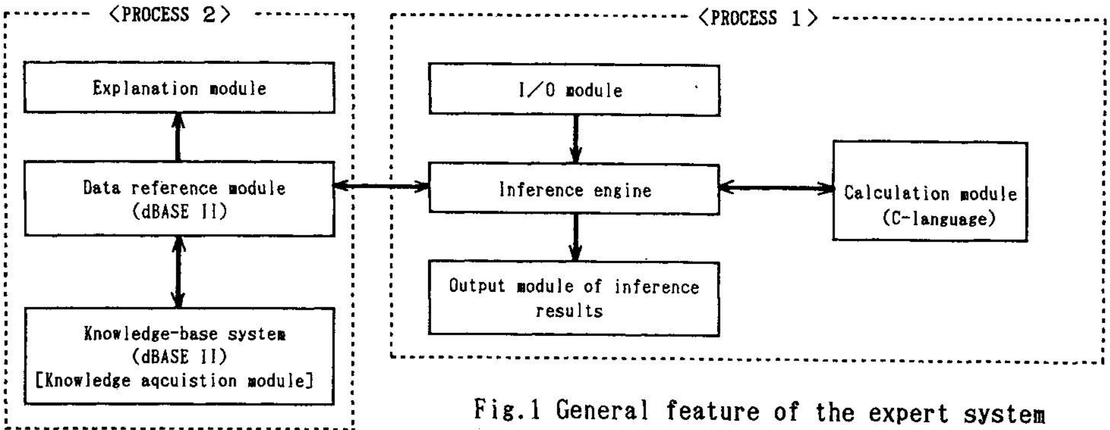

Fig.1 General feature of the expert system

2.1 Establishment of Rating Process and Treatment of Subjective Information

To develop a practical knowledge-based expert system for serviceability rating of concrete bridges, it is necessary not only to establish a diagnostic process model that can capture most of the available information about bridge rating but also have a rule in dealing with subjective information of bridge engineers such as professional experience, knowledge on bridge rating, etc.

In order to construct a diagnostic process model in the knowledge processor of the inference engine, the relations among causes of deterioration of structural serviceability (judgment factors) are represented by a global hierarchical form which has serviceability for slabs and main girders, respectively as the final goal. As an example, Fig.2(a)&(b) illustrates a part of the hierarchy structure of rating process at the final stage and a sub stage for main girders. This means that the serviceability of a main girder(final goal) is evaluated by a combination of "load carrying capability" and "durability" which are the two highest sub goals(Fig.2(a)). The "degree of flexural cracks" which is one of the lower sub goals is evaluated with a combination of "degree of water leakage and free lime deposition", "degree of freezing and thawing action", "degree of corrosion progress of reinforcing bars", "corrosion level of reinforcing bars" and "degree of cracking" which are the five goals involving the evaluated results from eleven basic factors(Fig.2(b)). The hierarchy structure consists of 11 sub goals, 23 goals and 34 basic factors for slabs and 10 sub goals, 17 goals and 30 basic factors for main girders. On the other hand, in order to develop a rule in dealing with subjective information of bridge engineers, a concept of the basic probability according to the Dempster & Shafer's theory is introduced in the knowledge base of the Bridge Rating Expert System. The upper probabilities in the Dempster & Shafer's theory[1] to introduce experiences and knowledge accumulated into the knowledge base are obtained through questionnaires consisting more than 400 questions concerning both slab and girder sent out to bridge experts[2]. The knowledge base consists of general facts, a set of production rules for storing the empirical knowledge and a series of knowledge fields which is in the form : [<series of basic factors>, <series of conditions>, <series of basic probability; m({x})>, <series of message number corresponding to the explanation module>].

In determining the value of the above-mentioned basic probabilities, m({x}), it is deemed effective to base on opinions extracted from questionnaires sent out to bridge rating experts as the bridge engineer's knowledge is considered to be transferred to the knowledge base of the expert system. Considering the case when a group of bridge experts make a diagnosis on a structure, the scattering of individual diagnosis may be regarded as the fuzziness of diagnosis by the group, which may be measured quantitatively by the standard deviation in the case of numerical estimation of the specified factor of a target structure. As an example, the questionnaire has a format in which each item is rated with points ranging between 0 to 100 and the following marks were added as notes:

25 : danger(possible necessity of repairs or strengthening)
75 : safe (nothing to be anxious about)
50 : moderate (middle of the two values above)

The questionnaire consists of a series of more than 400 questions which corresponded to the hierarchy structure of rating process for both slab and main girder. By using the average value and the standard deviation obtained by questionnaire results on each item, the soundness of a bridge, $\mu(x)$, will be given by the following equations:

$$\mu(x)=\exp[-\{(x-x_{ave})/\sigma_L\}^2] \qquad (x \leqq x_{ave})$$
$$\mu(x)=\exp[-\{(x-x_{ave})/\sigma_R\}^2] \qquad (x \geqq x_{ave}) \qquad (1)$$

where, x_{ave} is the average value, σ_L is the standard deviation of left side and σ_R is the standard deviation of right side.

Furthermore, the results of bridge rating are considered to be represented by five elements expressed by the linguistic expressions "safe", "slightly safe", "moderate", "slightly danger" and "danger", each of which is symbolized by **a**, **b**, **c**, **d** and **e**. The upper probability which reflects the element to those linguistic expressions is characterized by the soundness of a bridge as follows:

$$p^*(\{a\})=\mu(25)/\alpha,\quad p^*(\{b\})=\mu(37.5)/\alpha,$$
$$p^*(\{c\})=\mu(50)/\alpha,\quad p^*(\{d\})=\mu(62.5)/\alpha,\quad p^*(\{e\})=\mu(75)/\alpha \qquad (2)$$

where, p^* is the normalized basic(upper) probability and $\alpha=\max\{\mu(25),\mu(37.5),\mu(50),\mu(62.5),\mu(75)\}$

Fig.3 illustrates the relationship between the soundness of a bridge and the upper probability. When the average value, X_{ave} is greater than 75 points and less than 25 points, $\mu(x)=1.0$ is assigned to the upper probability for "safe" and to the upper probability for "danger", respectively.

The 15 kinds of basic probabilities can be obtained by solving the following equations which were formed based on the properties of basic probability:

$$
\begin{aligned}
&m(\{a\})+m(\{a,b\})+m(\{a,b,c\})+m(\{a,b,c,d\})+m(\{a,b,c,d,e\})=p^*(\{a\})\\
&m(\{b\})+m(\{a,b\})+m(\{b,c\})+m(\{a,b,c\})+m(\{b,c,d\})\\
&\qquad +m(\{a,b,c,d\})+m(\{b,c,d,e\})+m(\{a,b,c,d,e\})=p^*(\{b\})\\
&m(\{c\})+m(\{b,c\})+m(\{c,d\})+m(\{a,b,c\})+m(\{b,c,d\})+m(\{c,d,e\})\\
&\qquad +m(\{a,b,c,d\})+m(\{b,c,d,e\})+m(\{a,b,c,d,e\})=p^*(\{c\})\\
&m(\{d\})+m(\{c,d\})+m(\{d,e\})+m(\{b,c,d\})+m(\{c,d,e\})\\
&\qquad +m(\{a,b,c,d\})+m(\{b,c,d,e\})+m(\{a,b,c,d,e\})=p^*(\{d\})\\
&m(\{e\})+m(\{d,e\})+m(\{c,d,e\})+m(\{b,c,d,e\})+m(\{a,b,c,d,e\})=p^*(\{e\})\\
&m(\{a\})+m(\{b\})+m(\{c\})+m(\{d\})+m(\{e\})+m(\{a,b\})+m(\{b,c\})\\
&\qquad +m(\{c,d\})+m(\{d,e\})+m(\{a,b,c\})+m(\{b,c,d\})+m(\{c,d,e\})\\
&\qquad\qquad +m(\{a,b,c,d\})+m(\{b,c,d,e\})+m(\{a,b,c,d,e\})=1.0
\end{aligned}
\tag{3}
$$

Table 1 shows an example of calculation results of basic probability based on some items of the questionnaires.

In the rating process of structural serviceability conformed to the hierarchy structure, the combination of some basic probabilities retrieved from the series of knowledge fields are performed in each level of goal and sub goal. To unify the basic probability, the Dempster's rule of combination[1] is expressed as the following equation:

$$
m(A_k)=\frac{\displaystyle\sum_{A_{1i}\cap A_{2j}=A_k} m_1(A_{1i})\cdot m_2(A_{2j})}{1-\displaystyle\sum_{A_{1i}\cap A_{2j}=\phi} m_1(A_{1i})\cdot m_2(A_{2j})}\quad (\text{where, } A_k\neq\phi)
\tag{4}
$$

And, the rating at the final stage will be performed by selecting the element a_i which corresponds to the maximum estimated value $M(a_i)$ given by the following equation and then the judgment is given on the screen display of the system:

$$
M(a_i)=\sum_{a_i\in A_k}\frac{m(A_k)}{N(A_k)}\quad (i=1,2,\cdots n)
\tag{5}
$$

where, $m(A_k)$ is the basic probability for the set A_k and $N(A_k)$ is the number of elements in a set A_k.
Furthermore, since it may be considered that the degree of fuzziness is larger when a large mass of basic probability is able to move in a wider range, the fuzziness, F, of the assessment will be given by the following equation:

$$
\begin{aligned}
F&=\sum_{A_k} m(A_k)\cdot s(A_k)=\sum_{A_k} m(A_k)\cdot[\{N(A_k)-1\}\cdot dx]\\
&=\sum_{A_k} m(A_k)\cdot[\{N(A_k)-1\}/(n-1)]
\end{aligned}
\tag{6}
$$

where, $s(A_k)$ is the allotted movable distance for the basic probability of a set A_k and $dx=1/(n-1)$ is the distance between adjacent elements on the abscissa.

2.2 Flow of Inference

Both forward and backward reasoning are used as the inference engine in the present expert system shown in Fig.1. The flow of reasoning in the inference engine of the expert system is shown in Fig.4[3]. The inference is performed separately on the slab and the main girder of a target bridge aiming at the diagnosis of the serviceability as a final goal along the flow of Fig.4. Therefore, two kinds of knowledge-base system are prepared for slabs and main girders, and are read immediately before diagnosis starts.

In the flow of inferences shown in Fig.4, the forward reasoning process will continue until the arrival at the data item(basic factor) stage, for which the advanced inferences are difficult to perform. For example, an answer of "yes" or "no" for the deposition of free lime in reinforced concrete bridges halts any further inference. For such items(basic factors), suitable basic probabilities are assigned as an opinion from a series of knowledge fields and are joined

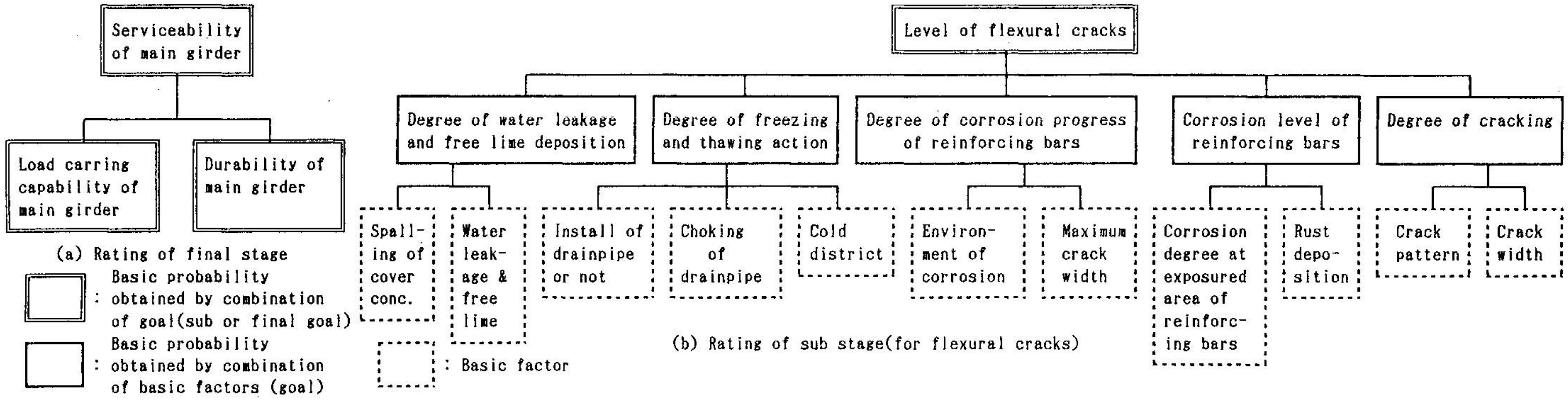

Fig.2 Example of hierarchy structure of rating process (for main girder)

Table 1 An example of calculation results of basic probability based on questionnaires

Case	Average score X_{ave}	Standard deviation σ_R σ_L	Basic probability														
			a	b	c	d	e	a,b	b,c	c,d	d,e	a,b,c	b,c,d	c,d,e	a,b, c,d	b,c, d,e	a,b,c, d,e
1	25.227	27.707 18.103	0.178	0.0	0.0	0.0	0.0	0.372	0.0	0.0	0.0	0.286	0.0	0.0	0.124	0.0	0.040
2	38.095	23.393 13.683	0.0	0.227	0.0	0.0	0.0	0.0	0.375	0.0	0.0	0.061	0.0	0.0	0.254	0.0	0.083
3	42.105	27.873 19.317	0.0	0.023	0.0	0.0	0.0	0.0	0.357	0.0	0.0	0.0	0.136	0.0	0.220	0.0	0.263
4	54.348	22.287 17.308	0.0	0.0	0.068	0.0	0.0	0.0	0.0	0.480	0.0	0.0	0.0	0.038	0.0	0.353	0.060
5	56.667	19.847 20.757	0.0	0.0	0.0	0.017	0.0	0.0	0.0	0.519	0.0	0.0	0.0	0.0	0.0	0.358	0.106

together at each goal. When all data reaches this state, forward reasoning will be followed by backward reasoning. The basic probability is given in a set of production rules for storing the empirical knowledge according to the results of questionnaires or to the subjective judgment on them. During backward reasoning, the lower sub goal, which is necessary for inference of the higher sub goals pre-set previously, is retrieved, and the assigned basic probabilities are calculated and combined, and next asserted as a new fact clause. At the same time, using the new basic probabilities obtained from the higher sub goal, the estimated values for "safe", "slightly safe", "moderate", "slightly danger" and "danger" with the fuzziness value which is the degree of subjective uncertainty are calculated and picked out as outputs. Finally, the serviceability of a target bridge, which is set as a final goal, is diagnosed basing on the combination of the two highest sub goals, namely the "durability" and the "load carrying capability", and is picked out.

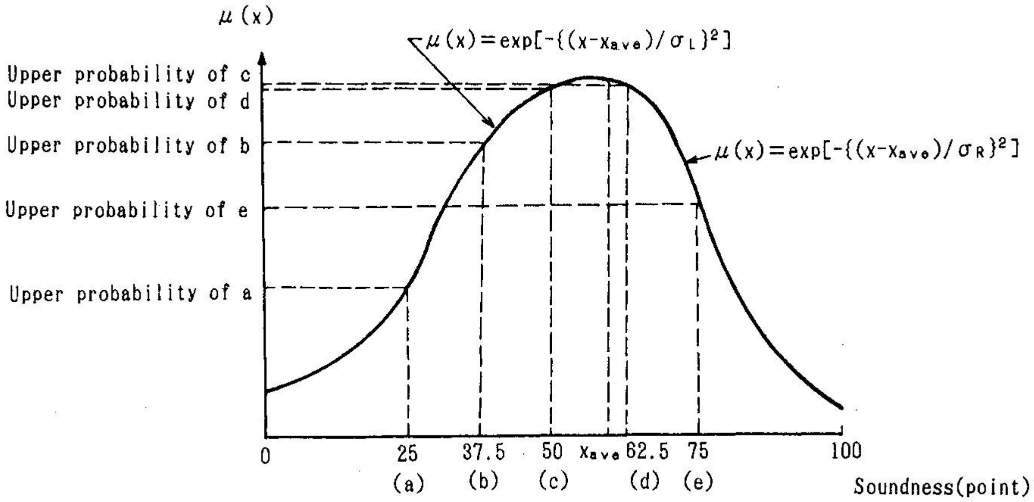

Fig.3 Relationship between soundness of bridge and upper probability

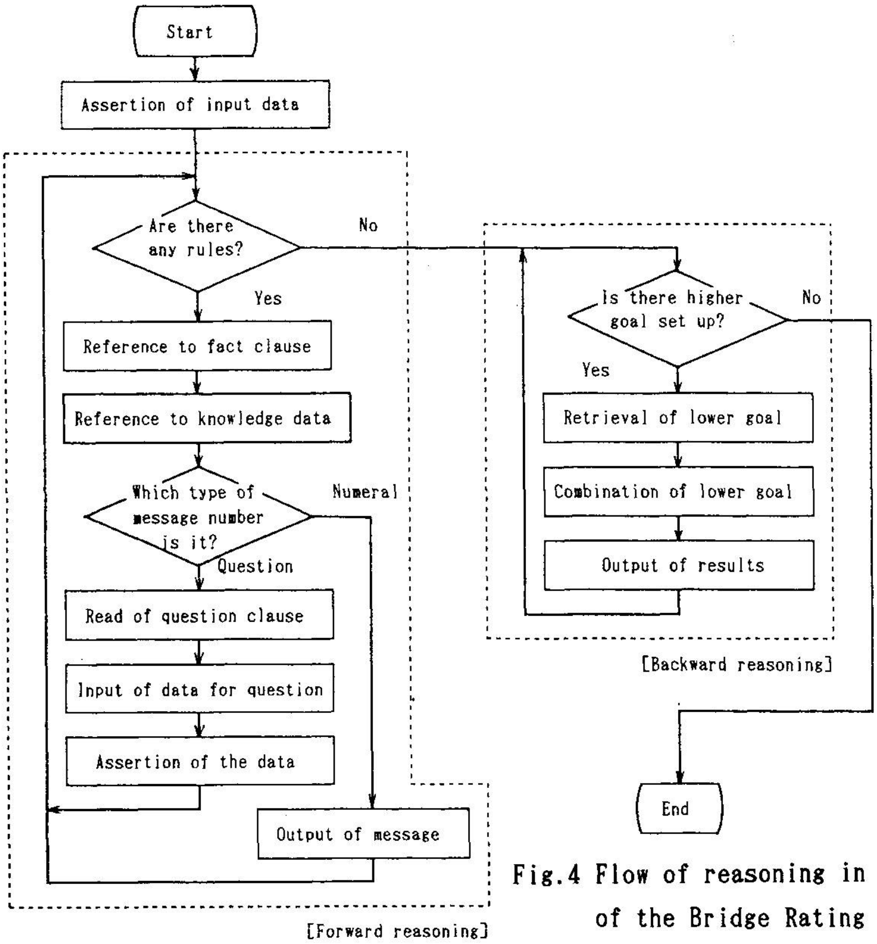

Fig.4 Flow of reasoning in inference engine of the Bridge Rating Expert System

3.APPLICATION OF EXPERT SYSTEM TO ACTUAL BRIDGE RATING

The Bridge Rating Expert System is verified for its effectiveness through the field testing on three kinds of reinforced concrete T-beam bridges[4].

3.1 Summary of Field Test Results

Three national highway bridges, Sakurabashi(constructed in 1933), Maenobashi(constructed in 1931) and Taitabashi(constructed in 1950), were selected for verification of the inference results because these bridges were about 40 and over 50 years old which is considered to be the design service life for concrete bridges. Table 2 shows the outline of the tested bridges.

3.1.1 Sakurabashi Bridge

Field observations show that the surfaces of each main girder were in poor condition where progressive deterioration due to cracks, spalls, water leakage, and free lime was observed. Especially, not only bending cracks but also shear cracks were found on side surfaces around the support. The maximum crack width of those cracks was more than 1.4mm. It was confirmed by means of the System Identification Method[4,5] on beam deflection under static test loading that the safety factors for shear failure of the main girder was lower than that of bending failure.

3.1.2 Maenobashi Bridge

Through superficial inspection of the main girders and slabs, cracks were not found unless approached closely, and factors affecting serious deterioration in durability and load carrying capability, such as the deposition of free lime and spalling of cover concrete were not observed throughout the structure except a few exposures of reinforcements. The bottom surface cracks of the slabs had a characteristic of being unidirectionally spread out with a maximum crack width of less than 0.1mm. On the other hand, bending cracks were found on the surfaces of each main girder and were generally less than 0.2mm in the maximum crack width. It was confirmed that the safety factors for the main girders for bending failure was smaller than of shear failure. Taking these into account, it was inferred that the girders and slabs were still in relatively sound condition which is similar to the superficial inspection results, namely, the soundness of Maenobashi bridge was judged as being approximately between "moderate" and "safe" with a small scattering. Material tests performed in a laboratory after the bridge site testing showed that the carbonation depth from the surface had an average value of 6.45cm. This figure shows that the durability of Maenobashi bridge is seriously low and special care has to be taken to check the increase of corrosion rate of the reinforced bars at cracked portions of the beams even though the bridge is not located in a corrosive environment.

3.1.3 Taitabashi Bridge

The bridge was located with the downstream surface facing the open sea. A progressive deterioration in the bottom surface cracks of slabs due to reinforcing bar corrosion was found during field observations. This assumption was based on the fact that a few rust deposition and free lime were observed on cracks throughout the structure. The maximum crack width in slabs was generally less than 0.3mm. And also, on the main girders, not only bending cracks but also corrosion cracks were noticed especially on the downstream surface. The maximum

Table 2 Outline of tested bridges

Bridge Name	Sakurabashi Bridge	Maenobashi Bridge	Taitabashi Bridge
Location	Mikazuki-cho,Sayou,Hyogo	Tanto-cho,Izushi,Hyogo	Hamasaka,Mikata,Hyogo
Route	Route 179	Route 426	Route 178
Total length	21.84m	45.80m	49.00m
Span	2@10.9m	5@9.16m	5@9.80m
Width	6.75m	5.50m	5.50m
Construction	1933(repaired in 1968)	1931	1950
Applied spec.	1926 Edition(2nd class)	1926 Edition(2nd class)	1939 Edition(2nd)
Bridge type	5 RC-T simple beams	4 RC-T simple beams	3 RC-T simple beams

crack width of those cracks was about 1.0mm. However, it must be noted that the bending effect was more dominant than the shear effect from the safety factor point of view. From these consideration, it was inferred that the girders and slabs were slightly danger condition, namely, the soundness of Taitabashi Bridge was judged as being approximately between "moderate" and "danger". The results of material test for concrete cores show that the compressive strength, the modulus of elasticity and the carbonation depth had an average value of $156kgf/cm^2$, $1.14 \times 10^5 kgf/cm^2$ and 3.65cm, respectively.

3.2 Rating by Expert System and Discussions

The Bridge Rating Expert System is used to diagnose the three bridges described above. As an example, Table 3 shows the description of the bridge which is the initial input data(basic factor) for Taitabashi bridge to the expert system. Table 4 shows an example of a dialog between the expert system and a user extracted from the intermediate stage of the diagnosis of reinforced concrete T-beams(main girders) in Taitabashi bridge. The first question produced by the expert system side to the user concerns the present state of cracks caused in main girders. In the case of Taitabashi bridge, the answer is chosen as "flexural crack", "corrosion crack", "bond crack" according to the observed eminent crack modes in the bridge. Generally speaking, the so-called menu format was adopted where the user selects an answer from prepared multiple-choice suggestions. The following question is on the flexural cracks on which the observation from the most severely cracked girder was chosen as input. The feature of the cracks pointed out in this case are generally unidirectionally spread out, which leads to the answer "3rd stage" out of a choice of 8 stages presented in a menu format. For the input of a maximum crack width of "1.0mm", which surpasses well above the allowable limit, the system recommends that the cracks be repaired. In the following step, the target of questions is directed to the "condition of cracks along the flexural crack", and answers concerning the severe deterioration around the bottom and both side surfaces are required: "Are there any water leak and free lime deposited? " or "Are there any spalling of cover concrete ?". The answers for these are "considerably occurred" and "slightly occurred", respectively. Based on the answer for level of spalling, a further question is produced by the expert system: "What degree of reinforcement corrosion is there". By answering "severely corroded", the questions on the flexural cracks comes to an end.

In the next steps, the target of questions is moved forward from "corrosion crack" to " bond crack", and the answers are requested to be prepared on the same manner as that of flexural crack. When all questions are filled up the data(basic factors), and the assigned basic probabilities are combined, the inference results with the inferred causes at the final goal and each sub goal are listed on the screen display through the forward and backward reasoning as shown in Table 5(a)-(c).

From these tables, the "slab serviceability" as the final goal inferred from the "load carrying capability" and the "durability" is estimated to be support of the

Table 3 An example of initial input data for Taitabashi bridge to the expert system

Bridge name	Taitabashi	Location	Harbor and seaside zone,
Total length	49 m		Cold district
Width	5.2 m	Widening of bridge	Span 1: carried out
Number of main girder	3 girders		Span 2: not carried out
Span of main girder	9.8m		Span 3: not carried out
Span of slab	1.575 m	Slope of approach	Gentle
Thickness of slab	Span 1: 14.6 cm	Traffic signal near approach	None
	Span 2: 16.7 cm	Crack or caving of	Span 1: present
	Span 3: 15.5 cm	road surface	Span 2: none
Bridge Age	38 years old		Span 3: none
Bridge type	Simple beam	Flatness of road surface	Almost flat
Cross section	T type	Traffic volume	Large
Size of cross section	Large	Percent of large-sized truck	Little
Supporting condition	Simple support	Vibration	Small
Differential settlement	None	Handrail	Small cross section
Applied specification	1939	Cross beam	.Present
Bridge grade	2nd grade	Drainpipe	None
		Forming of honeycomb & popout	Occured partly

element(see Eq.(2)) of "slightly safe" for Maenobashi bridge and "moderate" for Taitabashi bridge. On the other hand, the "girder serviceability" is estimated to be support of the element of "slightly danger" for Sakurabashi bridge, "moderate" for Maenobashi bridge and "slightly danger" for Taitabashi bridge. To illustrate further, we investigate and analyze the estimated values at the sub goals(judgment factors) where the items related to the deterioration of serviceability along the rating process for main girder are as follow: The estimated results for the "flexural crack", "shear crack" and "corrosion crack" in Sakurabashi bridge are support of the element of "slightly danger" and "danger". Then, such estimation affects those for the "whole damage of main girder(element value=0.93)", and the "load carrying capability" and the "durability", which are the highest sub goals and the "girder serviceability" which is the final goal are estimated to be support of the element of "slightly danger(element value=1.0)" without "fuzziness"(see Table 5(a)). On the contrary, for Maenobashi bridge, the estimated results for all judgment factors except for "service condition" have a tendency to support the element of "slightly safe" and "moderate". Then, the "load carrying capability" and the "durability" are estimated to be support of the element of "slightly safe"(see Table 5(b)). Finally, for Taitabashi bridge, the judgment factors except for "design", "execution of work" and "service condition" are estimated to be support of the element of "slightly danger" and "danger". Because such estimation affects those for the abovementioned three factors, both the "load carrying capability" and the "durability" are estimated to be support of the element of "slightly danger (element value=1.0)" without "fuzziness"(see Table 5(c)). These conclusions coincide well with the results obtained through the field testing[4].

Table 4 An example of dialog between the Bridge Rating Expert System and user (for main girder of Taitabashi bridge)

Question and explanation from the Bridge Rating Expert System	Answer from user
What kind of cracks are there in main girders?	Frexural crack Corrosion crack Bond crack
[C: Vertical cracks are inferred as caused by bending moment]	
What level is the bending cracks?	3rd stage; a few cracks
What is the maximum crack width?	1.0 mm
[C: Cracks over 0.3mm wide are recommended to be repaired]	
Are there any water leakage & free lime near the cracks?	Occurred considerably
Are there any spalling of cover concrete near the cracks?	Occurred slightly
What degree of reinforcement corrosion is there near the cracks?	Severely corroded
What level is the corrosion cracks?	3rd stage; a few cracks
[C: Horizontal cracks parallel to longitudinal direction are inferred as caused by volume expansion of steel corrosion]	
What is the maximum crack width?	0.5 mm
[C: Cracks over 0.3mm width are recommended to be repaired]	
Are there any water leakage & free lime near the cracks?	Occurred considerably
Are there any spalling of cover concrete near the cracks?	Occurred moderately
What degree of reinforcement corrosion is there near the cracks?	No exposure of steel
Are there any rust deposition?	Nothing
What level is the bond cracks?	3rd stage; a few cracks
[C: Small diagonal cracks along reinforcement sometimes occur when steel ratio is relatively large and round bars are used]	
What is the maximum crack width?	0.5 mm
[C: Cracks over 0.3mm width are recommended to be repaired]	
Are there any water leakage & free lime near the cracks?	Occurred considerably
Are there any spalling of cover concrete near the cracks?	Occurred moderately
What degree of reinforcement corrosion is there near the cracks?	No exposure of reinforcing bars
Are there any rust deposition?	Nothing

Table 5(a) Inference results for Sakurabashi bridge

	Judgement factor	safe	slightly safe	moderate	slightly danger	danger	fuzziness
Main girder	Design	0.132	0.313	0.437	0.115	0.003	0.466
	Execution of work	0.049	0.445	0.478	0.028	0.000	0.245
	Service condition	0.345	0.549	0.105	0.002	0.000	0.159
	Flexural crack	0.000	0.000	0.030	0.890	0.081	0.008
	Shear crack	0.000	0.000	0.000	0.081	0.919	0.002
	Corrosion crack	0.000	0.000	0.008	0.748	0.244	0.034
	Whole damage	0.000	0.000	0.000	0.929	0.071	0.000
	Load carrying capa.	0.000	0.000	0.000	1.000	0.000	0.000
	Durability	0.000	0.000	0.000	1.000	0.000	0.000
	Serviceability	0.000	0.000	0.000	1.000	0.000	0.000

Table 5(b) Inference results for Maenobashi bridge

	Judgement factor	safe	slightly safe	moderate	slightly danger	danger	fuzziness
Slab	Design	0.032	0.395	0.523	0.049	0.000	0.113
	Execution of work	0.248	0.248	0.248	0.248	0.008	0.760
	Road condition	0.993	0.007	0.000	0.000	0.000	0.003
	Service condition	0.985	0.015	0.000	0.000	0.000	0.003
	The worst slab	0.026	0.459	0.486	0.029	0.000	0.019
	Crack along haunch	0.277	0.581	0.131	0.011	0.000	0.285
	Crack at slab center	0.056	0.319	0.458	0.167	0.000	0.221
	Whole damage	0.007	0.634	0.357	0.001	0.000	0.006
	Load carrying capa.	0.000	0.442	0.558	0.000	0.000	0.001
	Durability	0.808	0.192	0.000	0.000	0.000	0.001
	Serviceability	0.001	0.999	0.000	0.000	0.000	0.000
Main girder	Design	0.132	0.313	0.437	0.115	0.003	0.466
	Execution of work	0.248	0.248	0.248	0.248	0.008	0.760
	Service condition	0.626	0.357	0.018	0.000	0.000	0.196
	Flexural crack	0.138	0.683	0.176	0.003	0.000	0.084
	Corrosion crack	0.001	0.093	0.599	0.306	0.000	0.000
	Whole damage	0.002	0.397	0.594	0.007	0.000	0.022
	Load carrying capa.	0.001	0.675	0.324	0.000	0.000	0.007
	Durability	0.001	0.789	0.210	0.000	0.000	0.003
	Serviceability	0.000	0.000	0.883	0.117	0.000	0.000

Table 5(c) Inference results for Taitabashi bridge

	Judgement factor	safe	slightly safe	moderate	slightly danger	danger	fuzziness
Slab	Design	0.007	0.317	0.605	0.071	0.001	0.068
	Execution of work	0.407	0.495	0.092	0.006	0.000	0.241
	Road condition	0.058	0.199	0.421	0.321	0.001	0.448
	Service condition	0.865	0.134	0.002	0.000	0.000	0.015
	The worst slab	0.000	0.000	0.001	0.515	0.484	0.003
	Crack along haunch	0.002	0.123	0.815	0.060	0.000	0.076
	Crack near support	0.000	0.007	0.173	0.794	0.026	0.068
	Crack at slab center	0.000	0.000	0.001	0.528	0.471	0.004
	Whole damage of slab	0.000	0.000	0.000	1.000	0.000	0.000
	Load carrying capa.	0.000	0.000	0.006	0.994	0.000	0.000
	Durability	0.000	0.000	1.000	0.000	0.000	0.000
	Serviceability	0.000	0.000	1.000	0.000	0.000	0.000
Main girder	Design	0.264	0.479	0.196	0.060	0.002	0.421
	Execution of work	0.049	0.445	0.478	0.028	0.000	0.245
	Service condition	0.511	0.455	0.034	0.000	0.000	0.178
	Flexural crack	0.000	0.000	0.000	0.009	0.991	0.001
	Corrosion crack	0.000	0.000	0.007	0.832	0.161	0.006
	Bond crack	0.000	0.000	0.078	0.915	0.007	0.020
	Whole damage	0.000	0.000	0.000	0.959	0.041	0.000
	Load carrying capa.	0.000	0.000	0.000	1.000	0.000	0.000
	Durability	0.000	0.000	0.000	1.000	0.000	0.000
	Serviceability	0.000	0.000	0.000	1.000	0.000	0.000

According to these inference results(element value and fuzziness) at sub goal and final goal levels, a consultation system for repair and rehabilitation techniques[6] is developed based on a combination of both the Bridge Rating Expert System and the Fuzzy Relational Data Base which deals with the subjective information related to the rating. The data base is divided into two main parts: 1) main girders and floor beams, and 2) reinforced concrete deck slabs. Moreover, each part is divided into three groups of data such as general bridge data, visual inspection and experimental data and also repair and rehabilitation background data. Each group of data includes 31 items such as bridge name, bridge proportion, etc. for general bridge data; 20 items such as crack pattern, corrosion of steel, deflection of girders, dynamic properties of slabs, etc. for visual inspection and experimental data; 11 items such as assessment results, applied repair or strengthening techniques, etc. for repair and rehabilitation background data. This data base has already been used to store the latest information for some 100 bridges and some 200 panels of reinforced concrete slabs in Hyogo Prefecture.

The details of these examinations will be reported in the near future.

4. CONCLUSIONS

By introducing the expert system and constructing the knowledge-base system of experiences and knowledge of experts through questionnaires to them, the systematization of the bridge serviceability diagnosis which is comparatively easy to modify and to renew is shown possible. This can be summarized as follows:

(1) The Bridge Rating Expert System, which is a computer-aided rating system, was newly developed based on a combination of both the hierarchy structure of rating process and the concept of the basic probability according to the Dempster & Shafer's theory which deal with the subjective informations related to the bridge rating for the construction of knowledge base system. And the final results produced by this system are considered to be represented by five elements expressed by linguistic expressions with the fuzziness value which is the degree of subjective uncertainty.

(2) Through the application to a few actual concrete bridges on which field data have been collected, reasonable results were obtained by inference with the system. The certification of the present system will be continued by accumulating data on actual bridges.

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On Aids to Interpretation in Monitoring Civil Engineering Systems

Aides pour la surveillance de systèmes en génie civil

Über Hilfsmittel bei der Auswertung der Überwachung der Systeme im Hoch- und Tiefbau

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SUMMARY
This paper reviews progress on the development of knowledge based systems to assist in the interpretation of signals from instrumentation. The instrumentation concerned is that used to monitor civil engineering structures or systems. Two examples are given. In the first, a signal derived from the non-destructive testing of a pile is characterised in a novel hierarchical way using a pattern grammar. The second uses data from embankment dams, and both rely on stored engineering experience in the interpretation process.

RESUME
Ce rapport présente les progrès dans le developpement de systèmes à base de connaissances pour assister l'interprétation de signaux émis par des instruments. Ces instruments sont ceux utilisés en génie civil pour surveiller des structures ou des systèmes. Deux exemples sont donnés. Dans le premier cas, le signal obtenu par l'examen non-destructif d'une fondation est classifié en utilisant un «pattern grammer» (une grammaire de modèles) sous forme de hiérarchie originale. Le deuxième utilise les informations recueillies de barrages. L'interpretation de chaque exemple est basée sur l'accumulation de connaissances techniques.

ZUSAMMENFASSUNG
Dieses Referat behandelt den Fortschritt in der Entwicklung der wissensbasierten Systeme bei der Auswertung von Signalen der Instrumentierung zur Überwachung von Strukturen oder Systemen im Hoch - und Tiefbau. Zwei Beispiele werden gegeben. Beim ersten wird ein Signal einer zerstörungsfreien Prüfung eines Pfahles hergeleitet, das auf eine neue hierarchische Weise durch Verwendung eines «Pattern grammar» charakterisiert wird, das zweite verwendet Daten von Dämmen. Beide verwenden für den Auswertungsprozess gespeicherte technische Erfahrung.

1. INTRODUCTION

The term "monitoring" when used in the civil engineering context can be applied to a wide variety of situations in which the "performance" of the thing under consideration is being examined. The term is meant to include the use of instrumentation, site investigation techniques and visual inspection.

Monitoring is carried out for two main reasons; to provide an assessment of the performance of an existing structure - feedback, and to provide information for future designs - feed forward. In both cases, as well as providing immediate information on the state of the system , the data provided is of vital importance to the validation of physical and theoretical models. The different types of monitoring often take place over different time scales. The feedforward type of monitoring, used for research as well as design purposes, tends to be more short term, while the feedback performance type of monitoring is usually long term or even permanent. There are exceptions to this generalisation of course. In one of the examples given in this paper, a short term non-destructive test is used to assess the integrity of a concrete pile.

The term performance is used here in its widest sense and is meant to include the safety and integrity of passive structures as well as the operating performance of for example water distribution or hydro-electric systems.

In most fields of civil engineering, monitoring is becoming more widespread. This is partly because of the need to maximise the economic performance of a system, partly because of increasing public demand for a "safe" environment, and also because the technology has advanced to a point where the required monitoring is both economically and technically realistic. However, although the instruments and associated computerised data acquisition have advanced considerably, the interpretation process has changed only a little. It is this area which needs attention.

One of the main difficulties hindering the effective use of monitoring is the management of the data produced.So much data is being, or can be, produced , and it is of such complexity and variety that it can become too much to handle [1],[2] . In such cases the data is filed away and never used. The purpose of this paper is to suggest aids in the process of data interpretation which will help in the overall management of the monitoring information.

2. CHARACTERISTICS OF CIVIL ENGINEERING DATA

The nature of the data collected from civil engineering monitoring is that it is peculiarly uncertain.The uncertainties arise in the way the data is collected,the types of systems being considered,the types of materials used and the methods of construction employed. Measurements taken are usually samples of parameters varying continuously in space and time. The measurements are often sparse in space, and may be irregular in time, requiring careful correlation and interpolation.The instruments used in the measuring process are often not measuring directly the desired parameter. For instance, to find stresses we often measure strains and then rely on an uncertain knowledge about prototype material properties. Also in a complex structure the desired parameter may be obscured by a more energetic effect. For example, in the case of the non-destructive pile test described below, the interpreter has to distinguish the signal due to internal sound waves from that due to surface waves when the pile is struck with a hammer. Other factors such as final instrument position or orientation add to the uncertainties.

Physical measurements form only a part of the monitoring process.A further ,and most important part includes visual observations and verbal descriptions of the current state of the system.These factors taken together make the use of conventional signal and data processing techniques of limited use.

3. INTERPRETATION

The sound interpretation of data requires a detailed knowledge of system being considered, and the types of instruments and data recording methods being used and must be based on proven engineering judgement and experience. The expert interpreter will also use background heuristic knowledge about past and present site conditions, the contractors involved in construction and a myriad of other odd bits of information. However, this is not always enough, even though he may have both "shallow" and "deep" knowledge about the systems, the human interpreter is limited by his ability to hold sufficient spatial and temporal correlations in his mind at one time.This can be illustrated by looking at the case of an embankment dam. Well instrumented dams may have several hundred instruments installed to produce a sparse spatial sampling of a number of parameters. A good dam engineer may be able to infer that certain events are happening because of a few particular signal characteristics. He can isolate parts of signals which have sudden changes, or which have flatter patches than expected, or he may detect such things as global drifts. He would certainly apply windowing in his analysis. However, pulling together all the little bits of evidence to provide an overview of the health of the dam is both very difficult and time consuming. A remarkable amount of dependable correlation does occur, but the engineer may be unable to explain his "hunches". This is a serious limitation when important safety decisions are being made.

It is interesting to note that the experienced engineer can form judgements based on the shape of the signal alone without reference to the numerical values. The shapes displayed to him are compared with models held in his mind, some of which are from a picture library assembled from previous experience, while others are made up at the time based on an understanding of the physics of the system.

Knowledge based systems can help in the interpretation process by;

(1) Compressing, handling and storing large amounts of data intelligently.

(2) Isolating important information

(3) Using the computers concentration and memory capacity to explore the data to infer relationships and highlight peculiarities

(4) Bringing together instrumentation data with qualitative data and stored background knowledge to provide inferences which can be explained.

Conventional methods of signal processing can help with the second of these points, but there are only a limited number of types of transformations which can be used and many of these are inappropriate for the sort of data usually found in the civil engineering context.

The third point can only be effectively tackled if there is a convenient means of representing the data in a form suitable for interfacing with the knowledge base.

In order to overcome both these difficulties a hierarchical method of presenting signal data has been developed which enables linguistic descriptions of the features of the data to be made.

4. HIERARCHICAL SIGNAL MANAGEMENT

The aims of the hierarchical signal management are two-fold. Firstly to present an intelligent compression of the raw data signal and secondly to present the compressed data in a form which can be readily manipulated by a knowledge base.

The first aim is achieved using vectors to represent segments of the signal, the second aim is achieved by describing strings of vectors in words .The words are then be assembled into formal structures for recognising features known as pattern grammars.

The processes described below were developed to assist in the interpretation of the signals produced in the in-situ testing of concrete piles[3] . The signals came from a geophone attached to the cap of a concrete pile after the head of the pile had been struck., figure 1.The figures used to illustrate the process refer to this situation.

4.1 Data Compression

The importance of signal shape has already been mentioned and these ideas are embodied in the methods described here. The signal is modelled both in terms of its shape, represented as a series of vectors, and its value represented as a series of steps. However only the hierarchical representation of shape will be considered in this paper.

The signal is first divided into sections of previously specified length. These sections are then classified as belonging to one of a number of limited classes of vectors. Figure 2 shows the vector space divided up into five classes. The vectors have the same length so that initially each section of the signal is specified solely by its shape class. A sensitivity factor is used to control the deviation of the vector representation from the original signal. If the deviation is too great the length of the vector is changed. This gives a two number code for each section of signal; class and length. The signal can then be portrayed either graphically or by a string of code numbers (figures 3, 4).

If there are any successive vectors of the same class these are concatenated and then the lengths are further classified so that the signal is eventually represented as a string of two digit codes.

The level of representation in the hierarchy is thus controlled by five parameters chosen by the user. They are (1) the initial length of the vector, (ii) the initial signed section length, (iii) the number of vector classes, (iv) the sensitivity factor and (v) the resolution of the final length classification. The resulting codes can then be operated on directly or output to a pattern directed inference system (PDIS), as in figure 3.

4.2 Pattern Grammars

Syntactic pattern recognition techniques have been used previously in such areas as medical electronics [4]. The idea is that an expert may be able to recognise complex features in a signal as being significant. If he is able to verbalise descriptions of these features they can be broken down into pattern primitives or basic shapes. The way these basic shapes are combined together to form higher level patterns is known as the pattern grammar. The grammar is specific to any particular recognition task.

In the case reported here the basic forms or pattern primitives are made up from various sequences of vector codes. An example is shown in figure 5.

The two processes described above enable representation of the shape of signals at multiple levels of detail. The level of detail chosen is that appropriate to the problem at hand. These processes can be viewed as changing the language of the signal from binary data to linguistic descriptions which are compatible with qualitative data and engineering knowledge contained in a KBS

5. INTERFACING WITH KNOWLEDGE BASED SYSTEMS

The other project mentioned earlier deals with the case of an embankment dam where there are many signals being recorded from a wide variety of sources rather than the one very confused signal given in the example above [5]. The work on this second project has considered a different way of characterising the time series data from the dam.

Although the pattern recognition techniques described in the example above are applicable to a certain extent in this second case, the expert is trying to detect patterns which represent deviations from norms rather than ones which will fall into predetermined classes. It is important in this kind of situation to avoid the trap of only looking for known faults, the system must be able to isolate conditions of which it has no experience.

A pilot system has been constructed using a numerical simulation of a zoned dam as the "input" with signals coming from eight piezometers in the core of the dam recording changes due to a fluctuating reservoir level. Figure 6 shows the arrangement of the instruments with typical signals. In this first stage, the signals were characterised using three global statistical measures of their behaviour. These were standard deviation, "uniformity" which gave an indication of discontinuities and "extremeness" which gave an indication of the dwell of the signal at maximum excursions from the mean. These characteristics were chosen after discussion with dam engineers as being most meaningful intuitively when scanning graphs of the data. It also enabled a rapid compression of say 200 data points into 3 characteristics. Two knowledge bases were then constructed using elicited knowledge and numerical simulations. The first knowledge base related the numerical values with the expected rarity of occurrence. Dam engineers were shown graphs of instrument signals and asked to classify them as not rare, moderately rare, very rare high or very rare low. These opinions were cross checked with a large number of runs of a dam simulation into which were injected artificial random errors.

The second knowledge base was used to determine how the rarity values of the individual characteristics should be combined to give an overall level of "cause for concern" for each instrument. It was constructed initially by hand. All the possible combinations were written down and values of cause for concern assigned to them. Later these relations were refined using an automated optimisation scheme operating on a training set of examples.

The resulting levels of cause for concern were applied to each individual instrument. It was considered vital that this information be presented pictorially to make the situation clearer rather than confuse it with yet more data. In this pilot scheme a picture of the cross-section of the dam was displayed with a shading pattern superimposed representing the level of concern at any point figure. The shading at each point was determined using an inverse low interpolation between the instruments.

The system can be interrogated about how it came to its conclusion about the level of concern using the screen cursor. In response, the system displays the concern level and the rarity levels for each of the characteristics of the instruments which dominated the assessment. Figure 7 shows a cause for concern map and a consequent interrogation.

Given the same initial signals experienced dam engineers were unable to come up with as succinct a description of the safety implications and had difficulty explaining the conclusions they did draw.

6. CONCLUSIONS

This paper has illustrated ways in which large amounts of instrumentation signal data can be intelligently compressed, handled and interfaced with knowledge bases for subsequent interpretation.

A pattern recognition type of signal processing system has been developed using a hierarchical vectorisation of the signals. Pattern grammars have been used to successfully describe and recognise features of signals from the non-destructive testing of piles.

A pilot system for the analysis of instrumentation from an embankment dam showed how even a simple characterisation can produce results which are more methodical and sensitive than those produced by a typical engineer.

7. ACKNOWLEDGEMENTS

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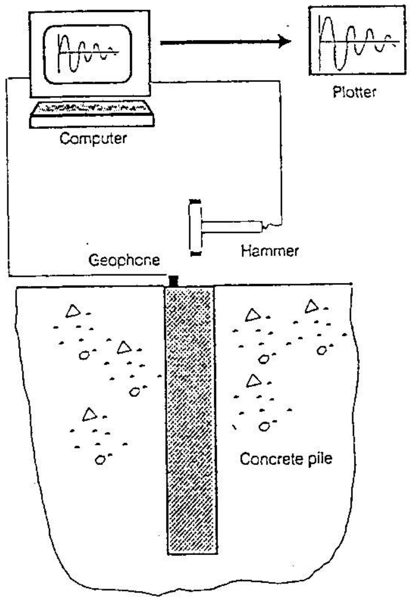


Figure 1 The non-destructive pile testing system.

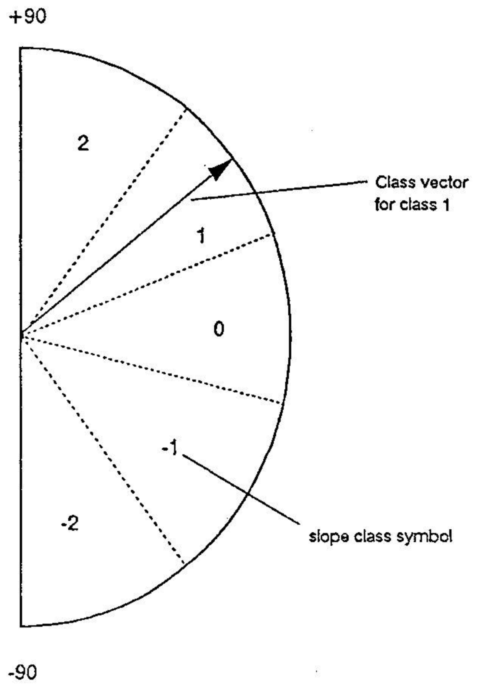


Figure 2 An illustration of the vector space divided into 5 classes.

slope class symbol	length time units
0	6
-2	30
-2	30
-2	30
0	30
1	30
2	30
2	30
1	30
2	30
1	30
-1	30
1	30
1	30
0	30
0	30
0	30
0	13

Initial coding
(a)

slope class symbol	length time units
0	6
-2	90
0	30
1	30
2	60
1	30
2	30
1	30
-1	30
1	60
0	103

Concatenated
(b)

slope class symbol	length class symbol
-2	3
0	1
1	1
2	2
1	1
2	1
1	1
-1	1
1	2
0	3

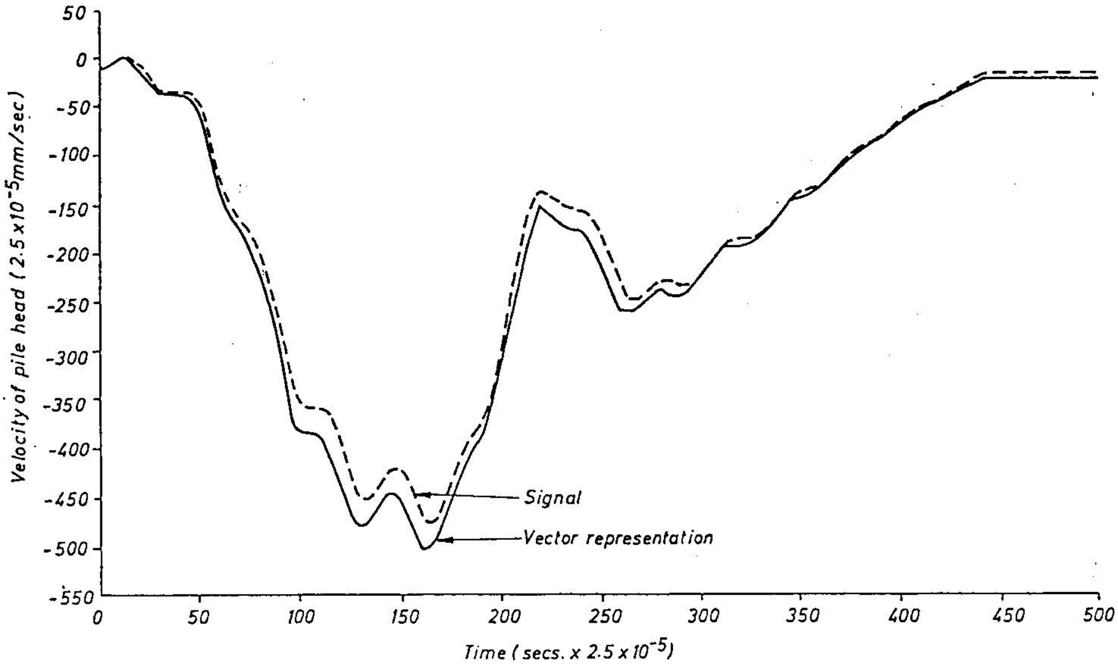
Lengths quantised
(c)

```
pile_med(pile_no,[
        -23,
          1,
         11,
         22,
         11,
         21,
         11,
        -11,
         12,
          3 ]).
```

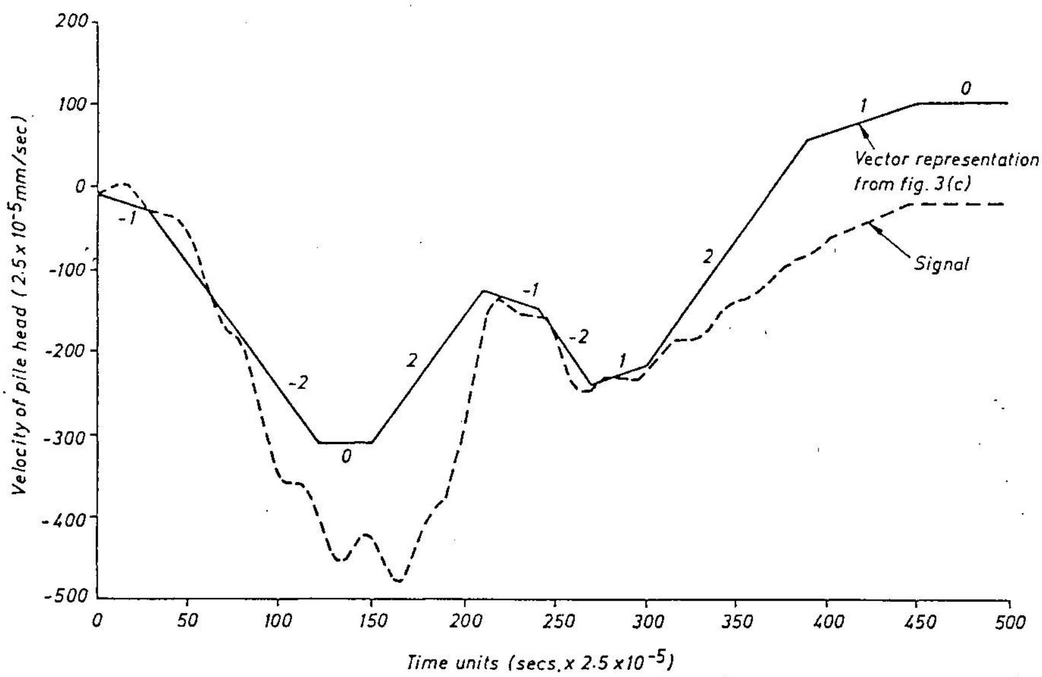
Chain code

PROLOG predicate
(d)

Figure 3 An example of the characterisation of signal from initial vectorisation to PROLOG predicate.



AN EXAMPLE SIGNAL : SHAPE REPRESENTATION
No. OF VECTOR CLASSES = 51
INITIALLY SPECIFIED LENGTH = 10 TIME UNITS
PRIMITIVE VECTOR LENGTH = 10 TIME UNITS



AN EXAMPLE SIGNAL : SHAPE REPRESENTATION
No. OF VECTOR CLASSES = 5
INITIALLY SPECIFIED LENGTH = 30 TIME UNITS
PRIMITIVE VECTOR LENGTH = 30 TIME UNITS

Figure 4 Representations of signal shapes at two levels in a hierarchy.

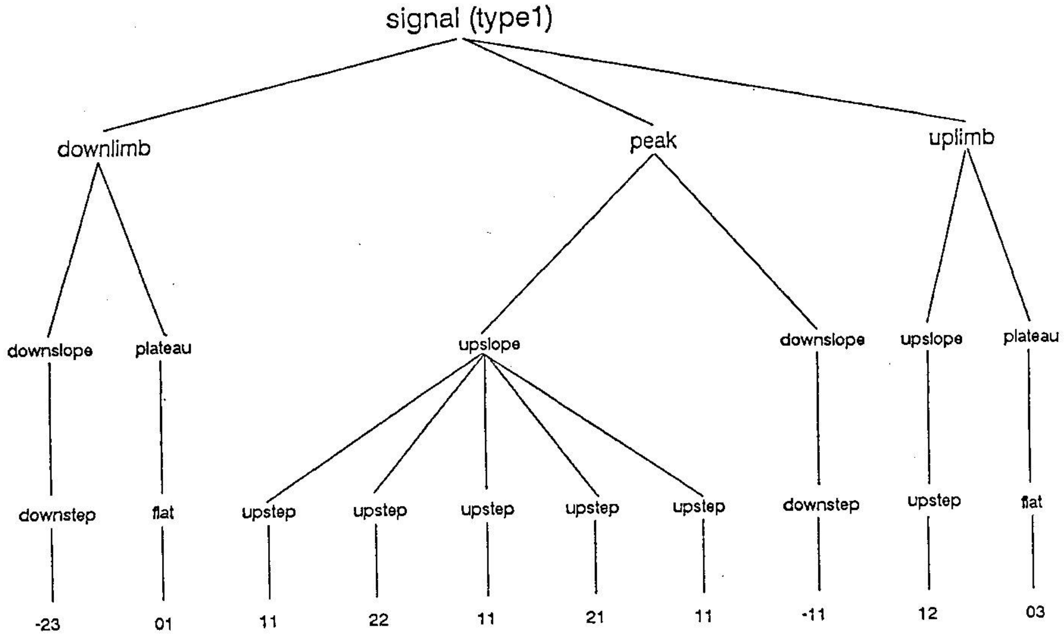


Figure 5 A Parse tree from the pile pattern grammar.

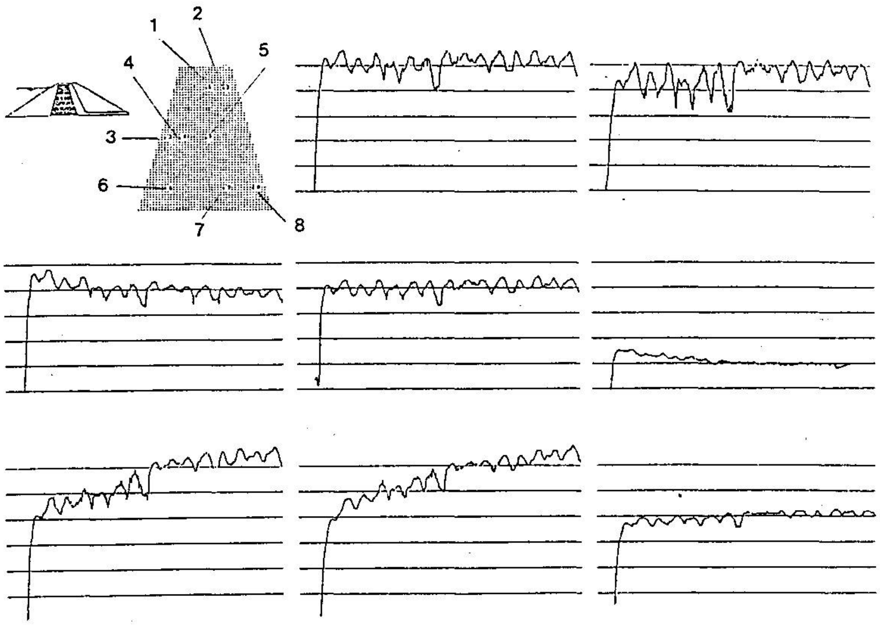
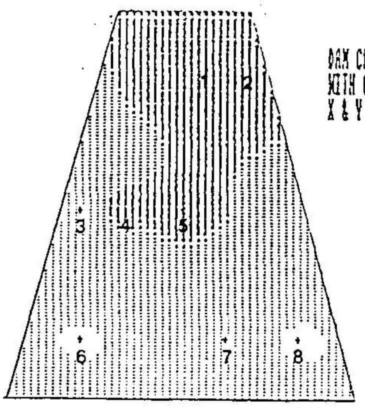


Figure 6 The model dam with typical instrument signals.



DAM CROSS SECTION
WITH CORE DETAIL SHOWING INSTRUMENTS
X & Y of interest?15,22

Concern at X= 15. & Y= 22. is 35.
All insts contribute (18.% except
INST No1.giving 13.% of case GMT concern =18.
INST No4.giving 25.% of case GMX concern =52.
INST No5.giving 34.% of case GMT concern =18.
INST No6.giving 15.% of case GQV concern =84.

MORE ?

>YES

WHICH INSTRUMENT IS OF INTEREST ?

>4

CONCERN GMX COMPRISES

A TYPICAL EXTREMENESS RATIO

A TYPICAL STANDARD DEVIATION RATIO

A VERY RARE HIGH UNIFORMITY RATIO

MORE ?

>NO

CONSULTATION ENDED

Figure 7 Typical output with an interrogation.