Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 68 (1993)

Rubrik: Session 4: Application to engineering diagnose and field management

SESSION 4

APPLICATION TO

ENGINEERING DIAGNOSE AND FIELD MANAGEMENT

Knowledge-Based System for Evaluating Earthquake Damage to Buildings

Système expert pour évaluer les dommages des bâtiments sous l'effet des séismes

Expertensystem für die Auswertung von Erdbebenschäden an Gebäuden

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SUMMARY

Two knowledge-based systems which have been put into operation are presented in this paper. The first can be used to predict earthquake damage to multistorey masonry buildings and the second can be used to predict earthquake damage to existing building stocks in ancity, to evaluate casualties and property losses, to identify high risk subareas and high risk building types, to decide the goal of disaster mitigation and its countermeasures. A wealth of domain knowledge is the prerequisite to develop the two systems and the manner of modelling after nature is the basic point of the knowledge engineering of the system.

RÉSUMÉ

L'article présente deux systèmes experts actuellement utilisés dans le cas de séismes, le premier servant à pronostiquer les dommages subis par les constructions en maçonnerie à étages multiples, l'autre permettant de prédire les dégâts subis par l'ensemble des bâtiments d'une ville, le nombre de victimes et les pertes subies en propriétés. Cela donne ainsi la possibilité d'identifier les zones à haut risque et les types d'immeubles particulièrement mis en péril, ainsi que de fixer les mesures et les objectifs destinés à réduire les dommages. Une base de données de connaissances exhaustives et une modélisation naturelle en matière d'ingénierie constituent les fondements du développement de ces deux systèmes.

ZUSAMMENFASSUNG

Der Beitrag erläutert zwei in Betrieb befindliche Expertensysteme, von denen das eine die Bebenschäden an mehrgeschossigen Mauerwerksbauten behandelt, während das andere dazu dient, den Schaden am Gebäudebestand einer Stadt, die Anzahl Opfer und die Verluste am Eigentum vorherzusagen. Damit können Zonen hohen Risikos und besonders gefährdete Gebäudetypen ausgeschieden und die Ziele und Massnahmen für die Schadensminderung beschlossen werden. Eine umfangreiche Wissensdatenbank und die naturalistische ingenieurmässige Modellierung sind die Grundlage für die Entwicklung der beiden Systeme.

1. INTRODUCTION

According to the experience of earthquake damage in China, casualties and property losses during an earthquake are mainly due to the damage to and collapse of buildings and the losses are much larger in city than in countryside, thus the prediction of damage to urban existing buildings is the basic work of earthquake prevention and disaster mitigation in China. Predicting earthquake damage to multistory masonry buildings, reducing and preventing the earthquake damage to this kind of building efficiently are urgent, protracted and strenuous works because multistory masonry buildings are widely used in China and they are easy to damage. Therefore, the expert system PDSMSMB−1 which can be used to predict earthquake damage to multistory masonry buildings and the intelligence aided decision making system PDKSCB−1 which can be used to predict earthcuake damage to existing building stocks in a city have been established during the research work on the prediction of earthquake damage to existing urban buildings and its countermeasures which belong to the important subject "the research on the application of intelligence aided decision making system to engineering" of the National Natural Science Foundation of China. The research work started from 1987 and the systems have been gone into application. It has been proved that the operation is efficient, the results are reliable, it has been reached expert level and have great sociological and economic benefit. The research work was sponsored by National Natural Science Foundation, State Seismological Bureau and Ministry of Construction of China.

The research object of PDSMSMB−1 system is to establish an expert system for predicting earthquake damage to multistory masonry buildings, to help common technicians to predict earthquake damage to this kind of buildings as the same level as the domain experts and make decision making analysis of earthquake resistance and disaster prevention reasonabl.

The research object of PDKSCB−1 system is to establish an intelligence aided decision making system for predicting earthquake damage to existing building stocks in a city and making its countermeasuers. The information of the predicting object and its environment are saved into computer to help people remember it accurately, manage it efficiently and process it fastly. The engineering knowledge and the experience of domain experts are saved into computer to help common civil technicians and managers of disaster prevention to predict earthquake damage, evaluate property losses and conduct decision making analysis of earthquake resistance and disaster prevention, to help the decision maker of goverment and relevant departments to make the goal of disaster mitigation and its countermeasures.

The relevant content of the two systems have been stated in reference [1]−[3] and [4]−[10]. The object of this paper is to expound something about the establishment of knowledge engineering and its application.

2. KNOWLEDGE SOURCE

According to the current Chinese aseismic criterion of buildings, the existing buildings are only evaluated whether they collapse or not under their fortifying earthquake intensity. According to the new aseismic design code of buildings(GBJ11−89), the damage degree of new designed buildings are limited to that the building can continue been used after repairing, the building are not damged under minor earthquake and not collapse under major earthquakr(the so called minor earthquake is about 1.5 grade lower than the fortifying intensity and the major earthquake is about 1 grade higher than the fortifying intensity). Both the aseismic criterion and the design code are in the light of giving the elements of building a basic requirement, mean while, in the vulnerability evaluation and the earthquake damage prediction, the buildings are handled as a system, and in the system, not only the affection of the elements themselves but also the affection of their mutual relation, interrestriction and interaction are considered. Therefore, to reach the object of this research, the domain knowledge of the two systems should go beyond the limit of the content of both the aseismic criterion and the design code, and the knowledge base of the two systems should be established not only according to the items of both the two standards.

The data and experience of earthquake damage espicially of multistory masonry buildings are very plentiful in China. Many experts of earthquake engineering experienced the site investigations from 1966 Xingtai earthquake to 1976 Tangshan earthquake, and many experimental research and theoritical analysis have been conducted. The research on prediction of earthquake damage to various kind of buildings was started from 1980's and the earthquake damage prediction are being conducted in hundreds of cities of China. Therefore, the two systems have a extensive knowledge source which includes the experience of earthquake damages and its statistical results, the research results of aseismic experiments and material property, general aseismic computation method and site affection, the corresponding items and content of aseismic design code and aseismic criterion, olso, the methods, experience and results in the earthquake damage prediction practice, the countermeasures to earthquake prevention and disaster mitigation in cities. The research group have been engaged in many practice of earthquake damage investigation, earthquake damage prediction and research works on disaster prevention, structural experiment and aseismic analysis for a long time, and participated to draw up the aseismic criterion, the design code and the guide to earthquake damage prediction, have plentiful expert knowledge and experience for establishing the two systems. Meanwhile, in the process of establishing the two systems, the research group also paied attention to absorbing the knowledge and experience of other experts, espicially those experts in the compilation groups of the aseismic criterion of buildings, the regulation of strengthening of aseismic buildings and the urban earthquake countermeasures. All of the knowledge above gave the two systems a extensive knowledge source.

3. DESIGN IDEOLOGY OF KNOWLEDGE ENGINEERING

A wealth of domain knowledge is the prerequisite for constructing applicable intelligence aided system. To design the knowledge engineering elaborately is the key to develop applicable intelligence aided system.

The knowledge engineering of the two systems is designed by domain experts themselves. Not rigidly adhere to common regulation and structural form, the design of knowledge engineering was taked great pains to "model oneself after natural" in order to reach the efficiency of "better than nature". Although the design is more difficult in this way, the constructed intelligence aided system can both reflect the knowledge, experience and logical thinking of domain experts and bring the techniqne of computer intelligence into full play. In this way, the intelligent system can reach the level of experts and have the function of intelligence better than experts.

For the design of knowledge engineering, the ideology of researchers in China and foreign country should be different owing to the difference of affection of their traditional thought. Take the landscape gardening as a example, the traditional gardening is regular landscape architecture in Europe and America, but the ancient landscape architecture of China had the greatest esteem for nature. When the expert system for predicting earthquake damage to multistory masonry buildings was researched by PRC–US cooperation, the writer of this paper gave the idea that the knowlege engineering (primary form) designed if according to the common formation of expert system at that time could not reflect the knowledge and experience of the domain experts, therefore designed a complicated network relationship according to the inference logic of domain expert. It looks as if exceed the technique of intelligence at that time and so not realized until the PDSMSMB–1 was constructed in 1988. We think that it is being pursuit with diligent care if the knowledge engineering is designed according to practical need and the expert system is constructed to be applicable instead of flourishing form, also, it is valuable, though it may be difficult and spend a long time.

The primary forms of knowledge engineering of the two systems in 1986–1987 were different. The knowledge base system of the PDSMSMB–1 which has a complete primary form, was partially substantiated and improved gradually, and extended from evaluation of earthquake damage to analysis of decision making; The block diagram of the PDKSCB–1 system was almost not changed from beginning, but the primary form was only a data base system, and it was developed into a knowledge base system in the practice and made the system extended from the prediction of status quo of buildings to developing prediction of future state and decision making goal of disaster mitigation. Therefore, it is quite necessary to substantiate, extend and improve the knowledge engineering in the developing process of intelligence aided systems.

4. KNOWLEDGE ENGINEERING FOR PDSMSMB–1

The system is divided into 6 parts, they are: information collection, experience inferece, computation analysis, earthquake damage prediction, seismic risk evaluation and result output.

4.1 Block Diagram

The block diagram of the system is shown in Figure 1 from which we can see that the earthquake damage to multistory masonry buildings is dependent on the future earthquake and defence state. The affection of the effective factors and site condition is considered in the defence state. For the evaluation of seismic risk degree, the vulnerability of the building, the damage degree and its acceptable degree and satisfaction degree to the three level of aseismic fortification according to intensity of 63%, 10% and 2–3% exceed probability of seismic hazard assessment in the next 50 years are synthetically evaluated, then, the decision making analysis whether the building is satisfid with the requirement of earthquake fortifying is conducted combining with present use of the building.

4.2 Information Collection

The information is collected by man–machine dialogue, the information includes 10 items, they are: ① present use, ② number of stories and neighbour relationship to other building, ③ kind of building structure, ④ status quo and construction age, ⑤ earthquake fortifying standard, ⑥ the property of structure, ⑦ whether the entirety is good or not, ⑧ the aseismic capacity of its wall, ⑨ the foundation, ⑩ site condition. There are three or more then three grades of sub–items for the continue of the information. A information card with its specification have been provided in order to save time in man–machine dialogue.

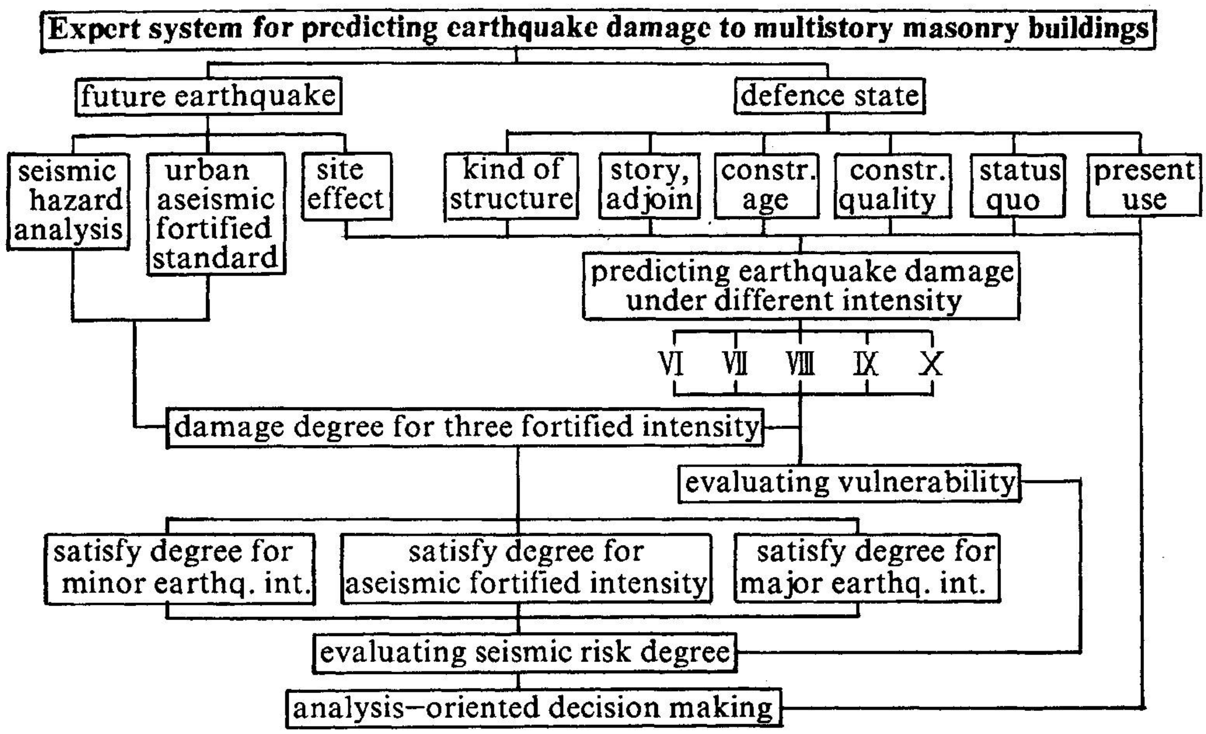

Figure 1. The block diagram of the expert prediction system PDKSCB–1

4.3 Experience Inference and Computing Analysis

The knowledge engineering of the system has been designed combine the calling of the knowledge base and digital computation with the logic inference. The data base and knowledge base are constructed by using as fas as possible the current analysis method and ready–made data espicially of the data of earthquake damage and its statistical results as the knowledge of fact and judgement, meanwhile the knowledge base and inference network are constructed by using the experience of experts as the knowledge of judgement and inference. The knowledge is expressed and the interrelation amoung information is processed by production rule, two dimensional table, modulus and nature network in the system. The uncertainty in the specific building and in the predicting process are expressed as method of expanding certainty coefficient, i.e., the uncertainty problem is implied in the deterministic inference process by using deterministic single value, multi–value and value range. The multi–value predicted results or evaluating range are realized by modifying the corresponding information or realized among the system.

4.4 The Evaluation of Earthquake Damage

The evaluation of earthquake damage in the system includes: the aseismic capacity analysis, predicting earthquake damage degree, evaluating vulnerabilty, casualties, economic losses, earthquake hazard and decision making analysis.

The aseismic capacity of multistory masonry building is marked by a synthetical coefficient K_i . The damage degree is divided into 6 ranks, i.e., basically intact, slightly damaged, moderately damaged, seriously damaged, partially collapsed and total collapsed, and they are marked as a earthquake damage index the range of which is 0–1.0. According to the aseismic capacity coefficient of each story and the earthquake damage index, the earthquake damage to longitudinal and transversal walls in each story can be expressed respectively, as 12 ranks in this system, from intact to collapsed.

Vulnerability is an inherent property of a building in a specific site. The vulnerability index is the weighted mean value of damage index of the building under the earthquake intensity of Ⅵ — Ⅹ with consideration of additional value of the affection of neighbour building..When the hazard is evaluated, the rate of casualties and economic losses is related to the damage index and type of building. The general earthquake hazard of the building is synthetically judged. The satisfying degree is divided into four ranks, i.e., ① very good ② ordinary ③ reluctantly and ④ not. The seismic risc degree is divided into 6 ranks, i.e., ① very small, ② quite small, ③ moderately(it can be accepted for common building), ④ slightly large(it can be reluctantly accepted for common building but it can not fit all requirements of the fortifying earthquake), ⑤ quite large(it can not be accepted), ⑥ very large. The decision making analysis is made according to vnlnerability and earthquake hazard degree for important building and common building respectively.

4.5 Output Results and its Inquirements

The system can provide a result report in a fixed form which includes 4 parts:

① The survey of the building. This is the predicting object formed in the information collecting process by the system itself. The users can modify the report about survey of the building in the screen of computer conveniently.

② The predicted results of earthquake damage. The earthquake damage index, the earthquake damage degree, the loss rate of the property in the building and the building itself and casualties under the intensity for Ⅵ — Ⅹ will be provided in a digital table.

③ The evaluation of vulnerability which includes vulnerability index, aseismic capacity and vulnerability evaluation.

④ The evaluation of earthquake hazard and decision making analysis. The satisfication degree with the requirements of 3 levels of fortifying intensity and the general comment will be provided.

If the earthquake damage index and phenomenon of the each story are inquired by users, the corresponding results will also be provided in table form.

4.6 The Realization of the System and Earthquake Example Inspection

The system is installed in IBM / AST microcomputer, the Chinese character is realized by Chinese character DOS system. It is compatible to operate in Eenglish and Chinese and the display and output is in Chinese. To solve the complicated network inference and large computation problem, the main program is wrote in FORTRAN language. The structure of the program is in card of patterns lump which is combined and managed by command file. The data base is constructed utilizing DBASE soft ware and the file manage ment and report compilation are conducted by calling the chinese character Wordstar. The batch processing function under the DOS is utilized to control and manage the system which has friendly interface which let the users can use the system rightly.

The system have been inspected by earthquake damages to masonry building in Tangshan, Haicheng, Tonghai, Yangjiang, Dongchuan, Wulumuqi earthquake, there is a good agreement between the predicted results and the data information from practical earthquake damage investigation and the agreement degree is 90 percent, the mean error is 0.1 degree of earthquake damage.

5. KNOWLEDGE ENGINEERING FOR PDKSCB–1

5.1 Block Diagram

The block diagram of the PDKSCB–1 system is shown in Figure 2. The system includes 3 subsystems, i.e., building, man–economic and diagram subsystem. The following results can be obtained.

① The predicted earthquake damage, casualties and economic losses in the whole city under given intensity Ⅵ, Ⅶ, Ⅷ, Ⅸ and Ⅹ, respectively, or / and under complete probability of seismic hazard assessment in the next 50 or some years.

② The predicted earthquake damage, casualties and economic losses of various subareas, and the identified high risk subareas.

③ The predicted earthquake damage, casualties and property losses of various types of building, and the identified high risk types.

④ The potential earthquake damage and risk distribution diagram in the city.

⑤ The possibility and condition of realization for the goal of disaster mitigation.

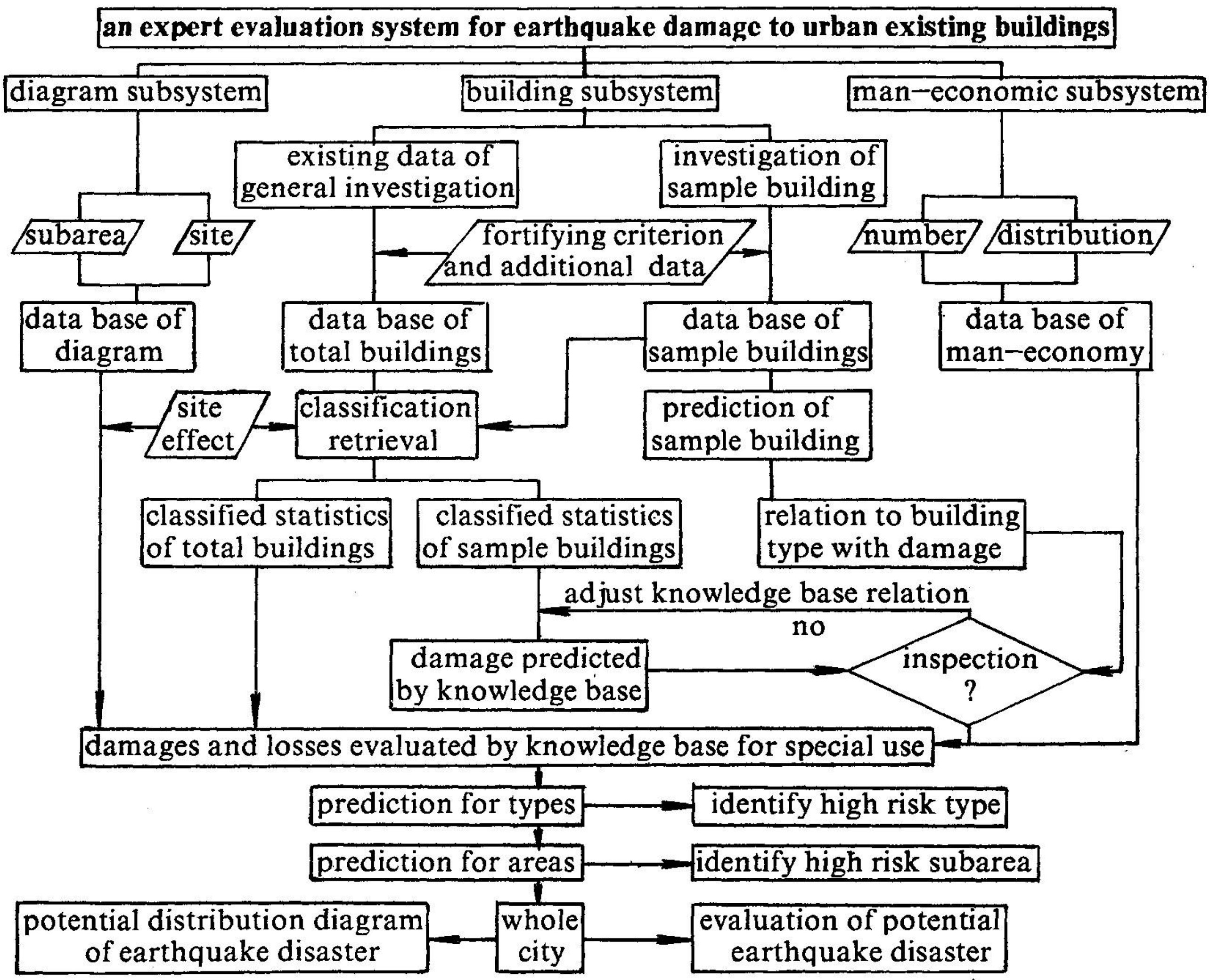

Figure 2. The block diagram of the expert evaluation system PDKSCB–1

5.2 Data Base

Collecting a large amount of data for predicting damage to existing buildings in a city and storing them up in a computer, the data base can be constructed directly or supported by knowledge base. Each datum is represented by a character string with a definite length, a digit code or a numerical value. There are six basic data bases in the system, ie., data base of buildings in the whole city, data base of sample buildings, data base of population, data base of property in building and value of building itself, data base of diagram and data base of site condition.

The type of a building in the data base is represented by 5 items, ie., kind of building structure, amount of the story, construction age, building status quo and present use. There are 6 kinds of structure, 9 kinds of story, 5 kinds of age, 5 kinds of status quo and 8 kinds of present use. The type of building can be retrieved either by one–element or multi–elememts. There are 33 types according to one–element retrieval and 10800 types according to 5–elements retrieval, but most of them in the 5–elements retrieval are empty sets, generally, there are only about one thousand types of building in a middle or big city.

5.3 Knowledge Bases

The evaluating earthquake hazard is considered to 5 effective factors , ie., earthquake effect, earthquake damage, economic losses, casualties and building importance. There are four major knowledge bases in this system.

①. Knowledge base for predicting damage to existing building. It is the basic and the largest knowledge base, in which the probability matrix of different damage degree under Ⅵ, Ⅶ, Ⅷ, Ⅸ, Ⅹ intensity for 10800 types of building according to 5–elements retrieval is constructed. Damage degree is divided into 6 ranks.

②. Knowledge base for evaluating direct economic loss. The losses are related to the damage degree and the earthquake effect and they are also related to factors for evaluating both the property in building and that of building itself, such as floor area, structure, stories, age, status quo and present use.

③. Knowledge base for evaluating casualty. The casualties are related to the damage degree and earthquake intensity and also related to the scale (floor area and type) of the building and occurred time (day or night).

The casualties or economic losses under given intensiy i are evaluated according to $P(D)_{ij}$ that is the predicting damage probability for the degree j under intensity i, and, under complete probability of seismic hazard assessment in the next 50 years is evaluated also.

④. Knowledge base for site condition. Some new knowledge bases in specific site condition can be constructed making use of the following formula, thus

$$P(D)_{ijs} = a_i P(D)_{(i-1)j} + b_i P(D)_{ij} + c_i P(D)_{(i+1)j} \qquad (1)$$

where s is the specific site, a_i, b_i and c_i are the coefficient of site condition and the sum should be equal to 1, if the effect of site exceed 1 grade for intensity, $(i \pm 1)$could be instead of $(i \pm 2)$or $(i \pm 3)$in the formula(1).

The knowledge base for predicting damage is constructed according to earthquake damage data, aseismic behavior analysis and experts′ experience. Because of considerable difference in aseismic capacity of same type of building in different cities, the key step to construct the knowledge base for special use is consistent inspection. Its means to let the earthquake damage to building samples predicted by the knowledge base for special use be identical to that predicted as building unit. It is controled by Hamming distance in two fuzzy sets, the distance of total deviation is limited in 0.02, the distance of point deviation is required to be less than 0.05, ie., 1 / 10 and 1 / 4 rank of damage degree, respectively.

5.4 Search of High Risk

To evaluate the potential earthquake risk, a synthetic decision analysis is conducted in the system based on 3 elements, ie., building damage, casualties and property losses. Each of the 3 elements is represented by 3 risk factors, ie., damage index, vulnerability index and easy damage probability for building damage, the number, rate and density for both the life and property losses. The high risk subarea is searched according to 9 undimensional risk factors which are obtained by dividing the 9 factors that have different dimension by their corresponding mean value of the whole city .

Identification of high risk type of building would be conducted in two steps, since the amount of building types is too many. The first step is searching vulnerability index reached threshold value. The search is conducted according to damage index, number of both the casualty and property losses under different intensity for minor, fortifying and major seismic state, respectively, as the second step. Denote the risk factor which reaches the threshold value as 1, otherwise as 0, summing up the risk factors which takes value of 1 or 0, the building type which summing number reaches 9 is the high risk building type and that reaches 5 to 8 is the next high risk building type.

5.5 Developing Prediction

The developing prediction is predicting earthquake damage to buildings, casualties and economic losses for some schemes of engineering measures and sociology countermeasures of disaster mitigation up to 2000 or a certain age accoroding to urban developing plan and experts' experience. From results of developing prediction, we can see for the goal of disaster mitigation and the decision making.

5.6 Input, Output and Display

The system is constructed in the IBM / AST microcomputer and the VAX / 780 computer, there are input, output and display in Chinese character. The system provides four types of user interface, including menu–driven interface, query interface, natural language explanation and graphics interface. Output of the system is a series of table in fixed form and can also represented by colour figure.

6. APPLICATION

The two systems have been widely used in China. PDSMSMB–1 system has been used to the earthquake damage prediction and / or aseismic appraisal and strengthening measure selection in nearly 20 cities. PDKSCB–1 system has been used in various cities from Sanmenxia city of 80 thousand population to Zhanjiang and Xiamen city of 300 thousand population and also to Taiyuan city of 1500 thousand population. The geographical positions of these cities are from Central Plains to south east sea bank, also to North of China, some of the sub–system have been also used in Wuxi city in south bank of Yangtse river and Tieling city in Northeast of China. The fortifying intensity of these cities are Ⅵ, Ⅶ, Ⅷ. It has been proved from the practical application that the reliability of the system is high, the decision making is efficient and applicability is strong, it will play its important role in improving the aseismic fortifying status and the public psychology status to earthquake.

7. CONCLUSION

The characteristics of the two systems are as follows:

①The wealth of domain knowledge is the outstanding characterization of this research. Therefore, the reliability of the two systems is high.

②The knowledge engineering is designed by domain experts themselves, model oneself after nature and make it better than nature are basis of the system. The system could fully reflect the knowledge, experience and logical thinking of experts, the inference is very natural, it can not only agree with the engineering concept, but also make use of the advantages of technique of computer intelligence.

③The two systems had been progressively developed, further improved and extended in the practice. PDSMSMB−1 system experienced primary form, demonstration stage, application stage and commercial stage; PDKSCB−1 system experienced man−machine system, moderate test and knowledge base system.

④The serving objects are clear, the content is complete and the usage is public. Both of the two system can be installed in microcomputer and operated in Chinese character.

This research also shows that it is efficient to develop intelligence aided decision making system in earthquake damage prediction domain. The two systems will be widely used and produce greater sociological and economic benefit in the International Decade for Natural Disaster Reduction.

REFERENCES

1. Yang Yucheng, An Earthquake Damage Evaluation System for multistory Masonry Buildings and its Application, World Information on Earthquake Eng., 1987.No3.
2. Yang Yucheng, et al, Earthquake Damage Prediction System for Multistory Masonry Buildings, Computational Structural Mechanics and Applications, Vol 6, No2, 1989.
3. Yang Yucheng, Li Dahua, et al, An Applicable Expert System for Predicting Earthquake Damage to Multistory Masonry Buildings, Earthquake Engineering and Engineering Vibration, Vol 10, No3, Sept., 1990.
4. Yang Yaling, YangYucheng, The Building Data Bank of Prediction Damage in a City, WIEE, 1988.No1.
5. Yang Yucheng et al, Application of a Man−machine System to Predict Earthquake Damage to Existing Buildings and Loss in Sanmenxia City, EEEV, Vol 9, No3, 1989.
6. Wang Zhishan, Yang Y.C Yang Y.L., A Search Technique for High Risk Building and High Risk Subarea in Earthquake Damage Prediction in City. WIEE, 1990. No4.
7. Yang Y.C., Wang Z.S., Yang Y.L., Yang Liu, An Intelligence Aided Decision System for Predicting Damage to Existing Buildings in City, EEEV, Vol 12, No1, Mar., 1992.
8. Yang Yucheng et al, An Expert system for Predicting Earthquake Damage to Urban Existing Buildings, Proceedings of International Symposium on Building Technology and Earthquake Hazard Mitigation, Kunming, China, March 1991.
9. Yang Y.C., Some Proposals for the Index System of Prodicting Earthquake Damage, WIEE, 1991.No4.
10. Yang Yucheng et al, An Expert Evaluation System for Earthquake Damage, Proceedings of 10th WCEE, Madrid, Spain, July 1992.

Predicting Debris Distribution of Collapsed Buildings

Pronostics sur la répartition des décombres de constructions

Vorhersage der Schuttverteilung einstürzender Bauten

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SUMMARY

In order to predict the earthquake damage and the influence on road transportation of the debris of existing buildings in future earthquakes, the software system named "Prediction Earthquake Damage and Debris Distribution in a City" is developed. The functions of the system, the description of the data, the debris accumulation model of collapsed buildings and the reasoning procedure are explained in this paper.

RÉSUMÉ

Cet article décrit un système de logiciels développé dans le but de prévoir la répartition des dommages dûs aux tremblements de terre futurs ainsi que l'influence des masses de décombres des immeubles écroulés sur les voies de circulation urbaine. Les auteurs exposent les différentes fonctions des logiciels, la description des données, le modèle d'accumulation des décombres des immeubles écroulés et le processus de raisonnement à suivre .

ZUSAMMENFASSUNG

Es wurde ein Softwaresystem entwickelt, um die Verteilung von Erdbebenschäden und die Auswirkung der Trümmermassen auf die Befahrbarkeit städtischer Strassen für künftige Beben vorherzusagen. Der Beitrag behandelt die Datenbeschreibung, das Modell der Schuttanhäufung einstürzender Gebäude und die Vorgehensweise beim Schliessen.

1. INTRODUCTION TO THE SOFTWARE SYSTEM —— PEDDD

In order to predict debris distribution of collapsed buildings during the earthquake, and to find out the influence of collapsed buildings both on road transportation and the rescue areas, the software PEDDD developed by Research Institute of Structural Engineering, Tsinghua University.Based upon it, Earthquake Resistant Office can organize a scientific aseismic and disaster relief plan and rescue scheme more effectively[1]. PEDDD can run on a micro–computer IBM PC / AT 286, 386 with graphics system or compatible. A digitizer and a plotter are needed. PEDDD consists of four functional modules as shown in Fig.1.[2]

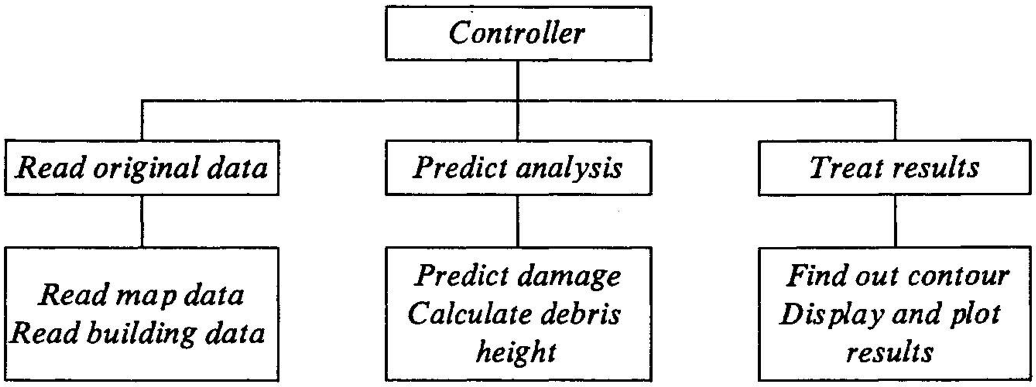


Fig.1 Functional modules diagram of PEDDD

PEDDD includes two characteristics: 1. In the earthquake damage, the accumulative effect of aftershock is considered, i.e. the effects of both the main shock and aftershock are all considered in PEDDD. 2. PEDDD has versatile graphics functions and make it easy to operate and to understand.

In order to realize the functions and characteristics of PEDDD, data and photographs from the surveys of post earthquake damage in many earthquakes in China and the ripe methods to predict earthquake damage in China are studied. These data, photographs and methods are turned into knowledge base described by computer. Finally,based on the earthquake damage prediction methods, the debris accumulation models and computer graphics technology, the objective of PEDDD is realized.

The approach of describing the building data and getting the debris accumulation type of a collapsed building will be explained in this paper.

2. REQUIRED PARAMETERS AND THEIR REPRESENTATION IN PEDDD

In the current version of PEDDD, two kinds of building i.e. multi–story masonry buildings and old brick timber buildings are considered. The selection and description of the parameters of a building are the keypoints during the process of prediction by computer.

Which parameters are required in PEDDD is determined by the applied methods which are come from the study of the surveys of the post earthquake damage in many earthquakes. The approach of getting the data of predicted buildings of PEDDD is to carry out the investigation of the existing buildings. Since the buildings are various and were built in different years, the data from the user may not contain all of them, i.e. it is impossible to get the accuracy initial parameters to predict.

In order to solve the above problem, the design maps of more than ten typical buildings are chosen to analyze and calculate. The basic data such as the weight per area and the wall percentage per area are obtained by statistics. It makes the work of getting initial data more rationally and rapidly. During the work of determining the parameters used in PEDDD, another contribution is to solve the determination of the existing station coefficient (the service condition coefficient) of the buildings. Because the coefficient of the situation of existing station of the building is a experience value evaluated by the experts, the method to get the coefficient in PEDDD is to consider the structural conditions of the building in different weight and to choose 12 factors to sum up in their weight. The coefficient is determined by using the sum to compare to the standard value.

After determining the required parameters of the building, the next problem is how to describe them in computer language. Based on the programming language Quick BASIC 4.5 used in PEDDD, the TYPE statement is used to solve it. There is a example to show how to describe the parameters in masonry buildings. The initial required parameters in predicting a masonry building which don't include the story information are 26. They are described as 'TYPE bricktype' in PEDDD. In the list of the explaining, 'non ' means the parameter is not a required initial one, it is needed in linking another information of the buildings.

```
TYPE    bricktype
      ibs       AS  INTEGER    ' the pointer looking for the building number
      itype     AS  INTEGER    ' the type of the building
      istory1   AS  INTEGER    ' non, link to the story information
      istory2   AS  INTEGER    ' non, link to the story information
      score     AS  SINGLE     ' the coefficient of the existing station of the building
      shape     AS  INTEGER    ' the shape of the building
      support   AS  INTEGER    ' the load-bearing system of the building
      time      AS  INTEGER    ' the time build the building
      slab      AS  INTEGER    ' the panel system
      roof      AS  INTEGER    ' the roof system
      max1      AS  SINGLE     ' the maximum distance between the adjacent transverse
      max2      AS  SINGLE        'wall in the top (max1) and bottom story (max2)
      l         AS  SINGLE     ' the length of the building
      w         AS  SINGLE     ' the width of the building
      column    AS  INTEGER    ' the situation of the constructed column
      beam      AS  INTEGER    ' the situation of the circle beam
      connect   AS  INTEGER    ' the situation of the connection between the
                                  ' longitudinal wall and the transverse wall
      brick     AS  INTEGER    ' the type of masonry block
      place     AS  INTEGER    ' the ground condition
      hp        AS  SINGLE     ' the height of the parapets
      area      AS  SINGLE     ' the area of the building
      sb        AS  INTEGER    ' there is a little house on the top or not
      ns        AS  INTEGER    ' the number of the story of the little house
      floor     AS  INTEGER    ' there is a shop in the bottom or not
      brick1    AS  INTEGER    ' the type of masonry block of the little house
      h         AS  SINGLE     ' the total height of the building
      g         AS  SINGLE     ' non, the total weight of the building from calculating
      owe       AS  SINGLE     ' non, the product of the l and w
      tw        AS  SINGLE     ' the thickness of the non load bearing wall
END   TYPE
```

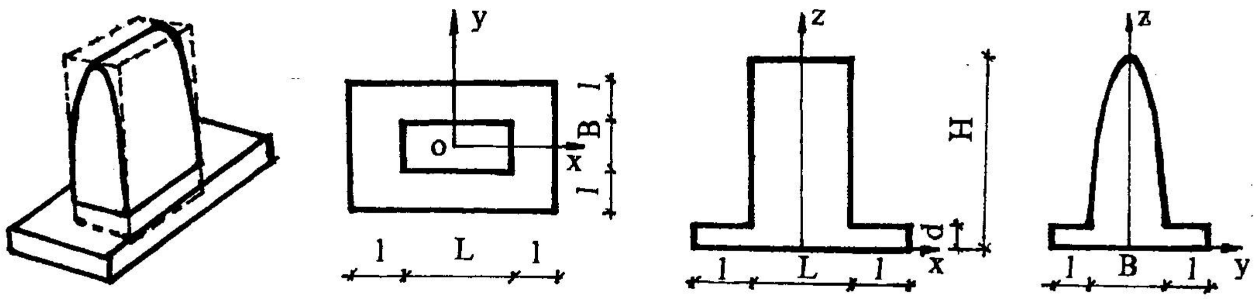
3. MODELS FOR DEBRIS ACCUMULATION OF COLLAPSED BUILDINGS

Based on the surveys of post earthquake damage of many earthquakes, especially on the photographs of TangShan earthquake[3], 1976, China and other eight strong earthquakes in China, the authors analyzed and summarized these photographs and data, then proposed three debris accumulation models to describe the shape and the distribution of the debris of the collapsed buildings. So far, only masonry buildings and old brick timber buildings are considered.

3.1 Accumulation model of partial collapsed buildings

In this case, the external longitudinal walls and gable walls are collapsed, but the transverse walls and internal longitudinal walls still exist. Sometimes, the falling of the external walls maybe cause the falling of the adjacent internal walls or the corner of the house partly collapse. Therefore, partial collapsed model mainly describes the characteristics of the collapsed external wall. The debris distribution sketch is shown in Fig.2. The shape of the collapsed building is described in the following Eq.(1).

$$Z = He^{-\left(\frac{y}{2B}\right)^2} \tag{1}$$



a) The shape b) The plan c) The section

Fig.2 Accumulation model of a partial collapsed building

To describe the debris that come from the collapsed wall, the average thickness d in the involved range l is used. Assume that the wall are broken one story by one story, distance l to the horizontal position of the debris of the top story can be determined by Eq.(2).

$$l = \sum_{i=1}^{n} h_i Sin(\frac{i\pi}{2n}) \tag{2}$$

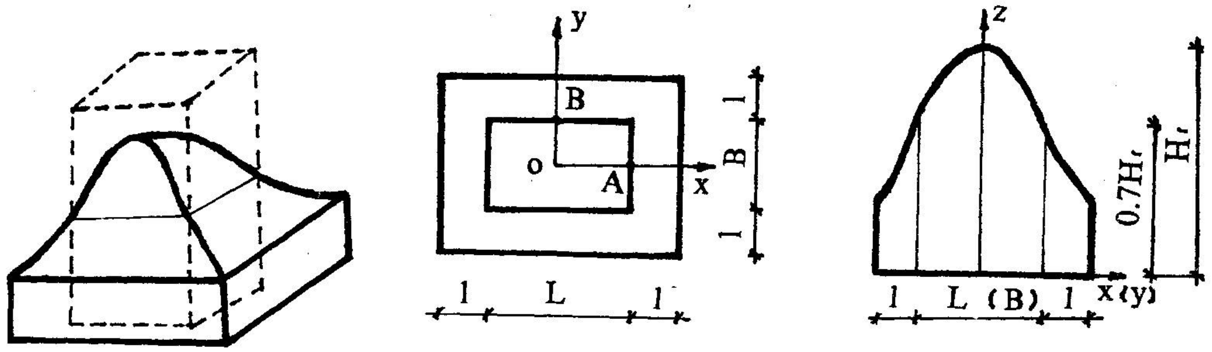
where n —— the total number of stories; h_i—— the height of the i–th story;
If $l > l_c$ then the final value is l_c , l_c is the nearest distance from the other adjacent buildings.

$$d = \frac{HW_d}{l} K_V \tag{3}$$

where W_d—— the thickness of the external wall;
H —— the total height of the building;
K_v—— the numerical coefficient with consideration of non–dense debris accumulation, for brick masonry buildings K_v= 1.5; for old brick timber buildings K_v= 2.0.

3.2 Accumulation model of overall collapsed buildings

Overall collapse means that a building is totally collapsed, or the falling of the bottom story lead to the building all collapsed. The debris graph is shown in Fig.3.



a) The shape b) The plan c) The section

Fig.3 Accumulation model of a overall collapsed building

The formula to calculate the height Z of the debris accumulation is described as Eq.4.

$$Z = H_f\, e^{-\left(\frac{x}{\alpha}\right)^2} e^{-\left(\frac{y}{\beta}\right)^2} \tag{4}$$

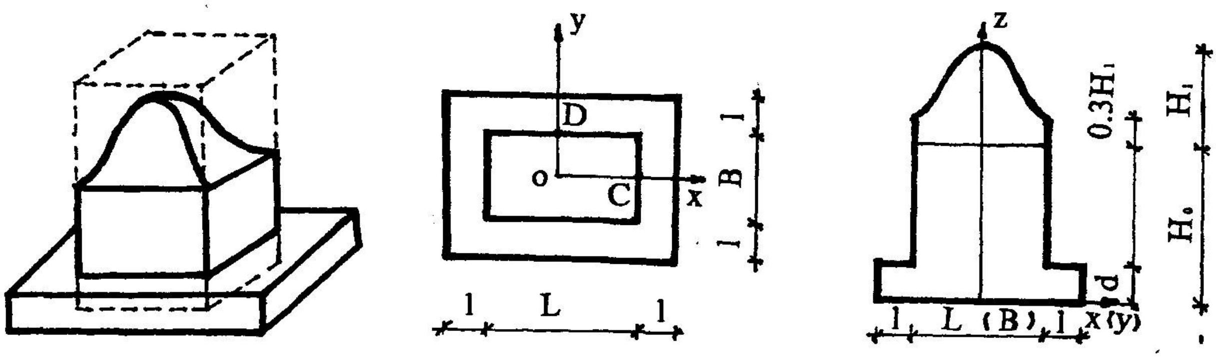
where α, β—— are the falling gradient along the x,y axis respectively. Assume that at the point A and B in Fig.3 , the height of the debris accumulation height is equal, and $Z = 0.7H_f$ then $\alpha = 0.837L$, $\beta = 0.837B$.

$$H_f = \frac{GK_V}{\gamma_{eq}\int_{\frac{L}{2}-l}^{\frac{L}{2}+l}\int_{\frac{B}{2}-l}^{\frac{B}{2}+l} e^{-\left(\frac{x}{\alpha}\right)^2} e^{-\left(\frac{y}{\beta}\right)^2} dxdy} \tag{5}$$

where G —— the total dead load of the building;
γ_{eq}—— the equivalent material volume weight;
l —— minimum of 0.5 H and l_c ;
K_v, H —— the same meaning as Eq.(3)

3.3 Accumulation model of top collapsed buildings

In this case, several stories of a building are collapsed. Nevertheless, other lower stories of this building still exist. The debris accumulation graph is shown in Fig.4. The height of debris accumulation can be expressed as Eq.(6). The thinckness of debris accumulation in the involved range *d* is determined by Eq.(7).



a) The shape b) The plan c) The section

Fig.4 Accumulation model of a top collapsed building

$$Z=\begin{cases} H_0+H_1 e^{-\left(\frac{x}{\alpha}\right)^2} e^{-\left(\frac{y}{\beta}\right)^2} & (\ |x|\leqslant 0.5L,\ |y|\leqslant 0.5B\ ) \\ d & (\ |x|>0.5L,\ |y|>0.5B\ ) \end{cases} \tag{6}$$

$$d=\frac{\frac{G'}{\gamma_{eq}}K_V-4\int_0^{\frac{L}{2}}\int_0^{\frac{B}{2}} e^{-\left(\frac{x}{\alpha}\right)^2} e^{-\left(\frac{y}{\beta}\right)^2}dxdy}{(L+2l)(B+2l)} \tag{7}$$

where H_0—— the height of the part building non–collapse;
H_1—— the maximum collapsed height;

$$H_1=\frac{G'K_V}{\gamma_{eq}BL} \tag{8}$$

and G'—— the weight of the part collapsed building;
α,β—— the same meaning as the Eq.4 . Assume that at the point C and D in Fig.4 , the height is equal and $Z = H_0+ 0.3H$, then in Eq.(6) $\alpha = 0.456$ L, $\beta = 0.456$ B.

4. REASONING PROCEDURE OF THE DEBRIS ACCUMULATION MODEL

4.1 The method to predict earthquake damage level

The kind of the debris accumulation of a collapsed building is deduced by the damage level. The debris accumulation model of partially collapsed building is gained from the partial collapsed building. Whether the accumulation models is the top one or the overall one is determined by the different collapsed degree of the overall building. Here two methods to predict earthquake damage level are introduced in brief.

4.1.1 Mutil–story masonry buildings

Refer to the reference [4], the ripe method to predict earthquake damage for multi–story masonry structure in China is applied in PEDDD. The suitable amendments are purposed when aftershock is considered. The keypoints of this method is to check the shear strength of the wall. The kernel thought is in the following:

The damage level of the buildings can be divided into six class: Basic no–damage, Slightly damaged, Moderately damaged, Seriously damaged, Partially collapsed and Overall collapsed. The classification is determined by the aseismic capability of the building. The main formula to represent the aseismic capability is Eq.(9).

$$K=K_{\mathrm{I}}\ K_{\mathrm{II}} \tag{9}$$

where K —— the aseismic capability index, represents the earthquake resistance capability of the masonry building in the given earthquake intensity.
K_{I}—— the aseismic strength coefficient of masonry building, obtained by calculating and comparing with the shear force of the building under the earthquake action.
K_{II}—— the secondly criterion coefficient. It is a revised coefficient considered other influenced factors on earthquake damage such as the connection, the existing station, the measure to strengthen the aseismic capability and the ground condition of the building.

Based on the above method and initial data of the masonry buildings, the aseismic capacity index of the each story of the building can be obtained. Using the following criterion in

Table.1, the earthquake damage level can be determined.

DAMAGE LEVEL	THE CRITERION	NOTES
Basic No–Damage	$K_0 > 1.0$	$K_0 = \underset{1 \leqslant i \leqslant n}{Min}\{K_{Ii}, K_{II}\}$ n —— the total stories of the building; N_0 —— the story number of unsatisfied aseismic capacity, if all are not satisfied then $N_0 = 2n$.
Slightly Damaged	$0.9 < K_0 < 1.0$	
Moderately Damaged	$0.6 < K_0 < 0.9$	
Seriously Damaged	$\frac{1}{3} \leqslant K_0 < \begin{cases} 0.6 & (N_0 > 1) \\ 0.7 & (N_0 > n/2) \\ 0.8 & (N_0 > 2n/3) \\ 0.9 & (N_0 > 3n/2) \end{cases}$	
Partially Collapsed	$K_0 < 1/3$ *and* $K_{Ii} \geqslant 1/3$	
Overall Collapsed	$K_0 < 1/3$ *and* $K_{Ii} < 1/3$	

Table.1 The Criterion to predict earthquake damage level

4.1.2 Old brick timber buildings

There is a little different in damage level classification between the old brick timber buildings and masonry buildings. There is no partial collapse damage level in old brick timber building. If the building collapsed then it should be overall collapsed.

The method used to predict old brick timber buildings is very different from the method in masonry buildings. According to the features of the earthquake damage in data, refer to the reference [5], probability theory and fuzzy mathematics technique are combined to predict earthquake damage for old brick timber structure. In this method, take the length, the existing station and the number of the stories of the building as the fuzzy number and build up fuzzy subset A . At the same time,from the extensive survey of the post earthquake damage form the fuzzy subset of earthquake damage index R . Therefore, according to the fuzzy relation $B = A\ R$, the value B which express the damage level will be obtained.

4.2 Reasoning procedure of debris accumulation model

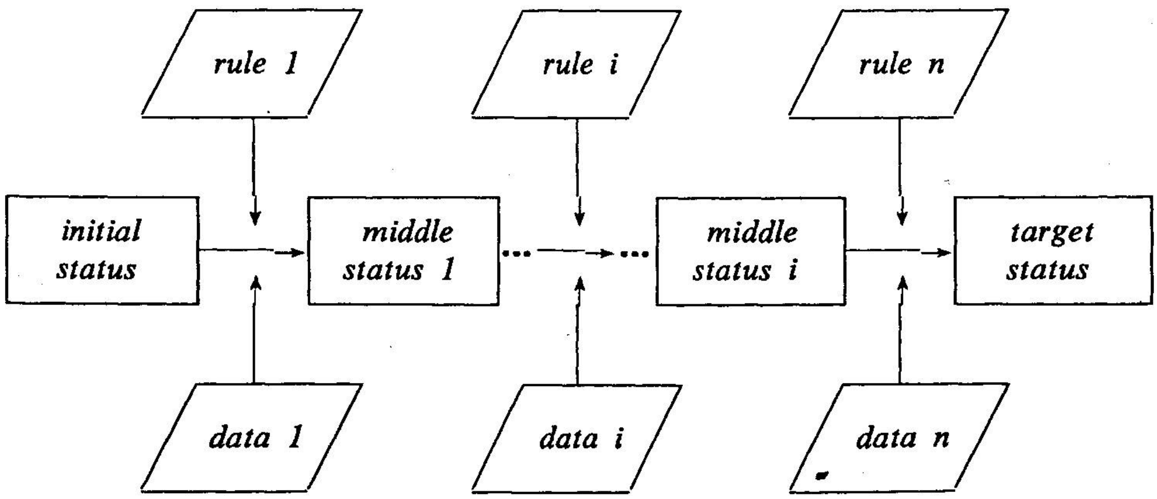


Fig.5 The reasoning procedure in PEDDD

In PEDDD, the following reasoning procedure is used. A reasoning path is formed by the driving status, the deductive method and the IF–THEN rule chains. Generally speaking, different initial data make the system use a suitable rule to obtain a approciate conclusion and to make the system be in different status. The current status will drive the system to choose another rule, be in another status, ..., and go on, until the earthquake damage level or the debris accumulation model is determined. The path can be shown in Fig.5.

5. APPLICATION AND CONCLUSION

In order to verify the reliability and practicability of PEDDD, the earthquake damage of the buildings which introduced in the collected data about TangShan Earthquake damage, is analyzed and 'predicted'. The results obtained are coincide with the true situation. Because the interface of PEDDD is friendly, operation is convenient, promptness and help are enough and error processing and maintenance are strong, user can use it very well. The application of PEDDD in two small streets of Yangpu District, Shanghai City where there are 1100 masonry or old brick timber buildings show the good reliability and practicability. It is quite promising to apply PEDDD in the seismic zone in China where multi–story masonry buildings and old brick timber buildings are crowded.

6. ACKNOWLEDGEMENTS

We acknowledge the contribution and assistance of the teachers and students of Research Institute of Structural Engineering, Tsinghua University. Especially Prof. Wang Jizhi, Prof. Qiu Zonglian, Mr. Fu Pinjun and students Ma Donghui, Sun Jiehua and Zhao WenDong. Also we are thankful for the support and cooperation of Mr. Xie Weizhou and others of the Earthquake Resistant Office for Disaster Relief Work of Yangpu District of Shanghai City of China.

REFERENCES

1. FENG SHIPING, MA DONGHUI, Research on Earthquake Damage and Debris Distribution of Earthquake Collapsed Buildings with Brick Masonry Structure and Old Brick Timber Structure, Research report of RISE, Tsinghua University, Dec.1991
2. WANG JiZHI, GUO HONGXIAN, SUN JIEHUA, Research Report on the Programming of PEDDD, Research report of RISE, Tsinghua University, Dec. 1991
3. YANG YUCHENG et al, The Method to Predict Earthquake Damage for Existing mutil–Masonry Building and its Reliability, EARTHQUAKE ENGINEERING AND ENGINEERING VIBRATION, P75–85, Sept. 1982
4. JIN GUOLIANG et al, The Method to Predict Earthquake Damage on Old Brick Timber Structure, ENGINEERING EARTHQUAKE RESISTANCE, P17–21, Jun. 1985
5. EARTHQUAKE DAMAGE ON TANGSHAN EARTHQUAKE, Seismic Press, May 1986

Damage Detection Using Artificial Neural System ·
Détection des dommages au moyen d'un système neuronal
Auffinden von Schäden mittels künstlichem neuronalen System

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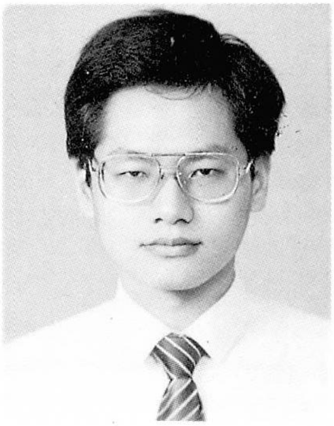

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SUMMARY
Artificial neural system is for inspecting the stiffness loss of each storey in multi-storey buildings with the data of the eigen value change rates. Each mode eigen value change rate is represented by an input unit and each story stiffness change rate is represented by an output unit. Training examples are randomly generated. The net is trained to achieve the machine learning purpose. Once the net is trained, the stiffness degradation of each story can be deduced by input of the measured eigen values of the damaged building. The learning result with various factors of inspected building and various factors of training examples are compared. The results show that the error rates of inspection of stiffness loss are dependent on these factors. Therefore, selection of these factors is important for minimizing the error rate.

RÉSUMÉ
Un système neuronal artificiel permet de déterminer la réduction de la rigidité de chaque étage de bâtiments à étages multiples, par suite du taux de changement de la fréquence propre. Le taux de changement de fréquence de chaque valeur propre correspond à une unité d'entrée du réseau, tandis que le taux de changement de rigidité de chaque étage équivaut à une unité de sortie. L'entraînement résulte d'exemples générés de manière aléatoire. Après avoir entré les valeurs propres mesurées sur le bâtiment endommagé, le réseau est apte à fournir la modification de rigidité. La comparaison des résultats d'apprentissage est faite à partir de divers facteurs des bâtiments inspectés et d'exemples résultant de l'entraînement. Les taux d'erreur du changement de rigidité sont fonction de ces facteurs, dont la sélection joue un rôle important pour minimiser le taux d'erreur.

ZUSAMMENFASSUNG
Es wird gezeigt, wie mit einem künstlichen neuronalen System in mehrgeschossigen Bauten der Steifigkeitsabfall eines jeden Stockwerks durch die Rate der Eigenfrequenzänderung bestimmt werden kann. Bei diesem Vorgehen entspricht die Frequenzänderungsrate eines jeden Eigenwerts einer Inputeinheit des Netzes und jede Steifigkeitsänderungsrate einer Outputeinheit. Das Trainieren des Netzes erfolgt durch zufällig generierte Beispiele. Die Lernergebnisse werden mit verschiedenen Faktoren inspizierter Gebäude und von Trainingsbeispielen verglichen. Die Fehlerrate hängt von diesen Faktoren ab. Ihrer Auswahl kommt grosse Bedeutung zu.

1. INTRODUCTION

Both of damage detection and damage assessment of existing structures become essential topics in structural safety. Many of papers [1-5] dealing with the damage assessment of existing structures by various methods such as energy absorbing potential by histeristic response loop of structure, seismic behavior affection, static or dynamic testing to identify the strength of the structures ...etc. End up to a quantified value called damage index or safety index. According to this index, more or less, information is provided to assist people to make some kind of decision such as the structural should be rebuilt, should be repaired or the structure can still be used as usual. However, once a structure has been assessed to be repaired. What should we do? First of all, detect the weak point, or the damaging region. Only after the damage point can be found, then the repairing process can be performed. Otherwise nothing we can do with the damaged structure.

How can the weak points be detected? People try to solve this problem by several points of aspects. For example, check the crack position by visualizing technique, detect the length and depth of the crack and assess the damage of structure subjectively; perform the dynamic tests to the existing structures and then calculate the stiffness of the structure globaly and locally through the structural identification techniques. Because of the issue dealing with highly nonlinear problems, it is very difficult to find the one to one function relationship between the structural behavior and the testing output such as the natural frequencies of the structure. Turns out the issue of the structural safety assessment usually become the collection of some subjective opinions. Where damage location is? still left unsolved.

In this decade, expert system become more popular to solve problems with complex interrelations between factors. Comments collected from experts are transfered to quantified index provide us relatively objective solution of the problems. When dealing with the problems such as damage assessment of existing structures, one of the primary obstacle is the set up of the knowledge base. Data acquisition or knowledge collection usually is an uneasy task. In order to overcome the bottle neck of knowledge acquisition, an artificial neural network (ANN) is employed as the learning mechanism to transfer engineering experience into understandable knowledge. In this paper, the effect of diagnosing damaged structures by artificial neural network is described.

For an existing structure, have been constructed and used for years, more or less damage would be existed to a certain level. Damage usually caused by some of abnormed forces such as earthquake, strong wind load ...etc. Dynamic tests provide data such as the natural frequencies in various vibration modes. An expert system software is employed to find the stiffness of the structure. However, whether the performance efficiency is high or not of the software rely on whether knowledge base is sound or not. To set up a strong knowledge base become an essential task.

Artificial neural system is a teachable system that consists of many simple units in a highly inter-connected network. Information is stored in the strength of the connections between units. ANS is modeled to simulate the gross structure of the brain: a collection of nerve cells, or neurons, where each of them is connected to as many as 10,000 others from which it receives stimuli-inputs and feedback, and to which it sends stimuli. The most famous artificial neural system model includes Back Propagation, Hopfield Net, Boltzman Machine, and so on [6-10].

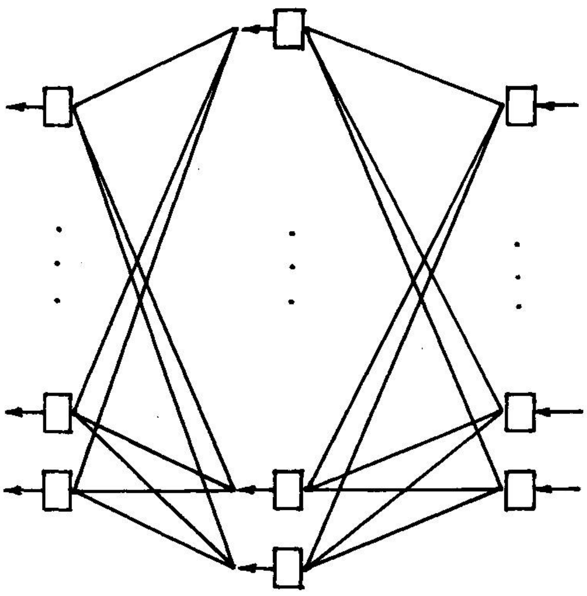
This paper describes an effort that applies ANS to inspect the location and degree of damage of the building. In this paper. Section 2 introduces artificial neural system model and the back propagation learning algorithm. Section 3 describes the method that employs artificial neural system to inspect the stiffness degradation of each story of a multistory shear building. In Section 4, several numerical examples are employed to illustrate and several remarks are concluded. Finally, Section 5 gives conclusion.

2. ARTIFICIAL NEURAL SYSTEM

An ANS is basically a system that uses simple processing units connected in a highly parallel manner. Some terminologies are introduced as follows:

Processing unit: Processing unit is an artificial neuron in a neural network. The output from one processing unit is fanned out and becomes the input to many other units.

Layered neural network: A layered neural network consists of several distinct layers of neurons (refer to Fig 1), including an input layer that employs sensor neurons to monitor external signals and an output layer that transmits signals to the external world. In addition, a layered network may contain one or more hidden layers. Hidden units are necessary to represent interaction of units and internal structures of the domain.
Connections: Connection is a signal transmission pathway between processing units. Each connection has a numerical weight that roughly corresponds to the influence between units. In general, all units in a layer are fully interconnected to the units in adjacent layers. Information flows unidirectionally from input layer through hidden layers to output layer. However, it flows in the reverse direction during learning.
Transfer function: Transfer function is a mathematical formula that determines a processing unit's output value as a function of the input signals and weights.
Learning algorithm: Learning algorithm is an algorithm that modifies the weights in connections according to the information it has learned.



$$U_j = \frac{1}{1+\exp(-\sum_k W_{kj}H_k)}$$

output layer units

links with weights W_{kj}

$$H_k = \frac{1}{1+\exp(-\sum_i V_{ik}S_i)}$$

hidden layer units

links with weights V_{ik}

input layer units

input value

Fig.1 A three-layer neural network.

In this paper, the type of network is a layered neural network using back-propagation algorithm as described by Rumelhart, Hiton and Williams [10]. The neuron cell receives a net signal of the linear weighted sum of all its inputs. A transfer function $1/(1+e^{-x})$ converts the net signal to output. The output, H_k, of the kth hidden unit is given by

$$H_k = \frac{1}{1+\exp(-\sum_i V_{ik}S_i)} \quad \ldots\ldots(1)$$

Where (a) V_{ik} is the weight on the link between the ith input unit and the kth hidden unit.
(b) S_i is the input value of the ith input unit.
Similarly, the output, U_j, of the jth output unit is given by

$$U_j = \frac{1}{1+\exp(-\sum_k W_{kj}H_k)} \quad \ldots\ldots(2)$$

where W_{kj} is the weight on the link between the kth hidden unit and the jth output unit.

The network learns by comparing its output of each input pattern with a target output T_j of that pattern, then calculating the error and propagating an error function backward through the net. The error function is defined as

$$E = \frac{1}{2}\sum_j (T_j - U_j)^2 \qquad (3)$$

Error function is the function of weights. For minimizing the error function, the gradient steepest descent method (Rumelhart et al. 1986) is employed. For a weight W_{kj}, the partial derivative of the error function is

$$\frac{\partial E}{\partial W_{kj}} = -U_j \cdot (1 - U_j) \cdot (T_j - U_j) \cdot H_k \qquad (4)$$

Then, the weight W_{kj} is modified by the incremental amount according to

$$\triangle W_{kj} = \eta \cdot (-\frac{\partial E}{\partial W_{kj}}) \qquad (5)$$

where η is called "learning rate" that gives the step size to minimize the error function. Let d_j be defined as

$$d_j = U_j \cdot (1 - U_j) \cdot (T_j - U_j) \qquad (6)$$

Then, the increment amount can be written as follows

$$\triangle W_{kj} = \eta \cdot d_j \cdot H_k \qquad (7)$$

In addition to the increment indicated in Eq. (7), a momentum term is often included in the formula to make the learning process more efficient. Consequently, the nth increment of weight W_{kj}, $\triangle W_{kj}^n$, is

$$\triangle W_{kj}^n = \eta \cdot d_j \cdot H_k + \alpha \cdot \triangle W_{kj}^{n-1} \qquad (8)$$

where α is the momentum factor.

For a hidden unit, d_k^* is defined as

$$d_k^* = H_k \cdot (1 - H_k) \cdot \sum_j (d_j \cdot W_{kj}) \qquad (9)$$

and the nth increament of the weight V_{ik}, $\triangle V_{ik}^n$, is

$$\triangle V_{ik}^n = \eta \cdot d_k^* \cdot S_i + \alpha \cdot \triangle V_{ik}^{n-1} \qquad (10)$$

According to Eq. (8) and Eq. (10), the strength of connections of newtwork would be modified iteratively to achieve convergence.

3. STRUCTURAL DAMAGE DETECTION

Artificial neural system is proposed to solve the problem of inspection of the stiffness loss of multistory shear building, i.e., to identify the damage location of the existing buildings. the central idea is as follows:

(1) Represent the eigen value chang rates of each vibration mode of the building by an input unit of ANS; represent the stiffness change rates of each story by an output unit of ANS.

(2) Generate training examples with simulation. Each example consists of a set of vibration mode eigen value change rates and a set of story stiffness change rates.

(3) Implement ANS learning to train the net by training examples.

(4) Measure the change rates of eigen values with instrument in real world, and input these value into the trained net, and then the change rates of story stiffness of the building can be deduced from the output of the net.

There are four phases for building an ANS mode, including:

(1) Identification phase: identifying the input and output of the net.

(2) Collection phase: collecting examples for training and testing.

(3) Implementation phase: implementing ANS learning to train the net by training examples.

(4) Verification phase: verifying the trained net by testing examples.

The detail procedure for using ANS to inspect structural damage is described as follows:

(1) Identification phase:
The definition of input of the ANS is defined as follows:

$$S_i = \frac{\lambda_i - \lambda_i'}{\lambda_i} \quad \text{(11)}$$

where S_i = the actual input of the ith input unit.
λ_i = the ith mode eigen value of the original building.
λ_i' = the ith mode eigen value of the existing building.
The definition of output of the ANS is defined as follows:

$$T_j = \frac{R_j}{D_{max}} \quad \text{(12)}$$

$$R_j = \frac{k_j - k_j'}{k_j} \quad \text{(13)}$$

where T_j = the actual output of the jth output unit.
R_j = the change rate of the jth story stiffness.
k_j = the ith story stiffness of the original building.
k_j' = the ith story stiffness of the existing building.
D_{amx} = the maximum stiffness loss rate.
For example, $T_j = 1$, denotes $k_j' = (1 - D_{max}) \cdot k_j$
$T_j = 0$, denotes $k_j' = k_j$

(2) Collection phase:
Training examples are generated with the following simulation procedure:
Set the of damaged story of the building, Prob $(0 < Prob < 1)$
Set the maximum stiffness loss rate, $D_{max}(0 < D_{max} < 10$
Set the number of story of the building, N_{floor}
Set the number of desired examples, N_{exam}
Set the number of desired mode, N_{mode}
Let $I = 0$
Repeat until $I = N_{exam}$
  Let $I = I + 1$
  Let $J = 0$
  Repeat until $J = N_{floof}$
    Let $J = J + 1$
    Generate a uniform random number, Random, in [0,1]
      if Random > Prob
      then $k_j' = k_j$
      else $k_j' = k_j \cdot (1 - D_{max} \cdot Random/Prob)$
  Analyze the N_{mode} lowest mode eigen values, and calculate the input and output of ANS by Eq. (11) and Eq. (12).
Testing examples can be obtained from the same procedure.

(3) Implementation phase:
After collection phase, ANS learning can be employed to train the net by training examples. In this phase several parameters need to be assigned, including (1) learning rate; (2) momentum factor; (3) number of hidden layers; (4) number of hidden units. The initial net weights can be assigned with uniformly distributed random values as follows

$$\text{initial net weight} = C_{weight} \cdot Random \qquad (14)$$

where C_{weight} = the multiplier factor of initial net weight,
Random = a uniform random number in the $[-1, +1]$ interval.

(4) Verification phase:
For evaluating the learning results, the error rate is defined as follows:

$$\text{error rate} = \sqrt{\frac{\sum (T_j - U_j)^2}{N_{out}}}, \text{ where } j = 1, 2, \cdots, N_{out} \qquad (15)$$

where N_{out} is the number of output units.

4. NUMERICAL EXAMPLES

A ten-story shear building shown in fig. 2 is analyzed, and several factors are set as follows:

A. factors of inspected building
(1) the rate of damaged story of the building, Prob =0.4
(2) the maximum stiffness loss rate, $D_{max} = 0.4$

B. Factors of training examples:
(1) the number of training examples, $N_{exam} = 500$
(2) the number of desired mode, $N_{mode} = 10$

C. Factors of neural network
(1) the learning rate, $\eta = 1.0$
(2) the momentum factor, $\alpha = 0.5$
(3) the number of hidden layers, $N_{layer} = 1$
(4) the number of hidden units, $n_{hidden} = 10$

The results of the implementation of the problem are shown in Fig. 3. It is found that the error rate is converged while training example set (i.e. 500 training examples) is implemented about 50 cycles. The results of several testing examples are shown in Table 1. The procedure takes about 5 minutes on a 80386 PC with math coprocessor.

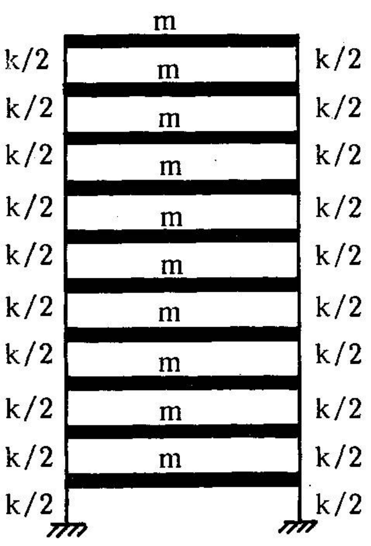


Fig.2 Ten-story shear building model of numerical example. ($m = 1.0 \cdot 10^5 kg$, $k = 2.0 \cdot 10^8 Nt/M$)

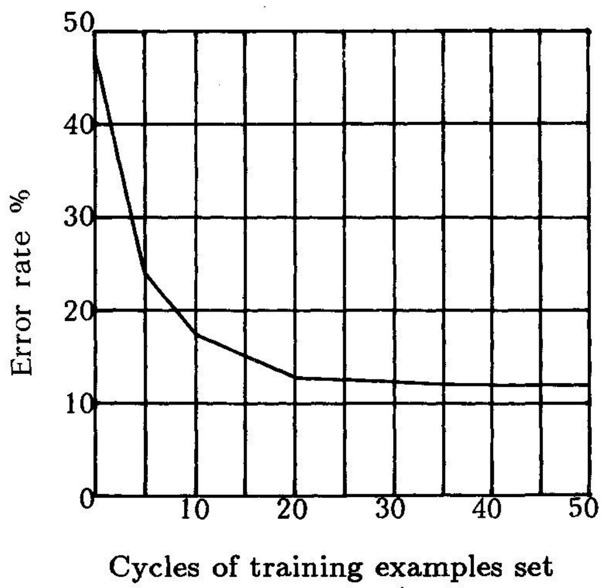


Fig.3 Learning results for cycles of training examples.

TABLE 1. The results of several testing examples.

Test Exam	Output unit									
No.	1	2	3	4	5	6	7	8	9	10
1	0.29	0.00	0.97	0.00	0.28	0.38	0.47	0.34	0.00	0.00
	0.12	0.00	0.93	0.08	0.29	0.60	0.48	0.47	0.02	0.02
2	0.00	0.77	0.65	0.69	0.30	0.99	0.00	0.30	0.00	0.00
	0.01	0.71	0.95	0.14	0.16	0.50	0.25	0.67	0.07	0.07
3	0.00	0.78	0.84	0.00	0.56	0.00	0.60	0.98	0.00	0.62
	0.01	0.47	0.93	0.02	0.82	0.11	0.75	0.95	0.05	0.48
4	0.00	0.96	0.81	0.61	0.00	0.00	0.00	0.23	0.00	0.28
	0.08	0.76	0.82	0.61	0.32	0.02	0.00	0.12	0.18	0.37
5	0.00	0.00	0.11	0.24	0.38	0.00	0.00	0.00	0.28	0.00
	0.01	0.02	0.05	0.14	0.56	0.01	0.00	0.03	0.26	0.01
6	0.30	0.00	0.00	0.00	0.03	0.09	0.00	0.00	0.00	0.00
	0.15	0.01	0.02	0.00	0.03	0.01	0.00	0.01	0.01	0.01
7	0.00	0.16	0.00	0.58	0.07	0.94	0.00	0.00	0.38	0.00
	0.02	0.10	0.08	0.52	0.03	0.97	0.02	0.08	0.27	0.09
8	0.00	0.00	0.00	0.00	0.08	0.95	0.00	0.00	0.00	0.23
	0.15	0.02	0.12	0.00	0.00	0.96	0.02	0.01	0.04	0.33
9	0.18	0.94	0.58	0.00	0.00	0.48	0.47	0.00	0.00	0.00
	0.09	0.81	0.26	0.04	0.27	0.85	0.03	0.01	0.13	0.07
10	0.54	0.00	0.00	0.95	0.00	0.00	0.59	0.01	0.00	0.00
	0.39	0.01	0.04	0.90	0.07	0.01	0.46	0.07	0.02	0.06

Note: The upper values are the actual output of the output unit.
The lower values are the inference output value of the output unit.

For the reason of comparison, the above mentioned implementation is reimplemented by the cases applying various factors. When each of the special cases with the change of certian mentioned factor is implemented, all of the other factors are maintained as the value set in above paragraph.

A. Factors of inspected building

(1) The rate of damaged story of the building, prob = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9. The results of the implementation are shown in Fig. 4.

(2) The maximum stiffness loss rate, D_{max} = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9. The results are shown in Fig. 5.

B. Factors of training examples:

(1) The number of training examples, N_{exam} =50, 100, 250, 500, 750, 1000, 1500, 2000. The results of the implementation are shown in Fig. 6.

(2) The number of desired mode, N_{mode} = 3, 4, 5, 6, 7, 8, 9, 10. The results are shown in Fig. 7.

From the above example, some observations can be given as follows

A. Factors of inspected building

(1)The rate of damaged story of the building

The results show that there is a increasing monotonical relationship between the rate of damage story of the building and the error rate.

(2) The maximum stiffness loss rate

The results show that there is a increasing monotonical relationship between the maximum stiffness loss rate of the building and the error rate.

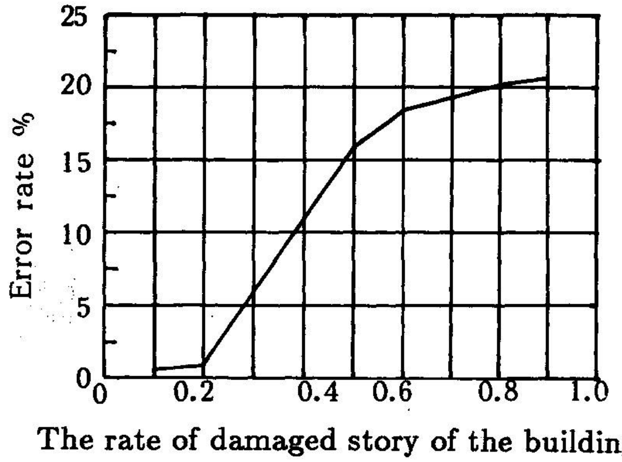


Fig.4 Comparison of the learning results with the rate of damaged story of the building.

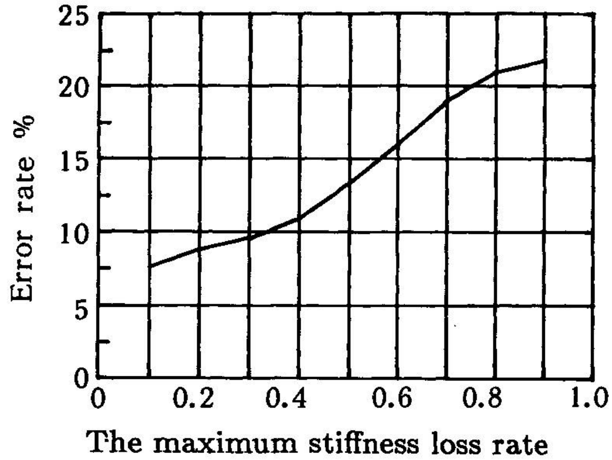


Fig.5 Comparison of the learning results with the maximum stiffness loss rate.

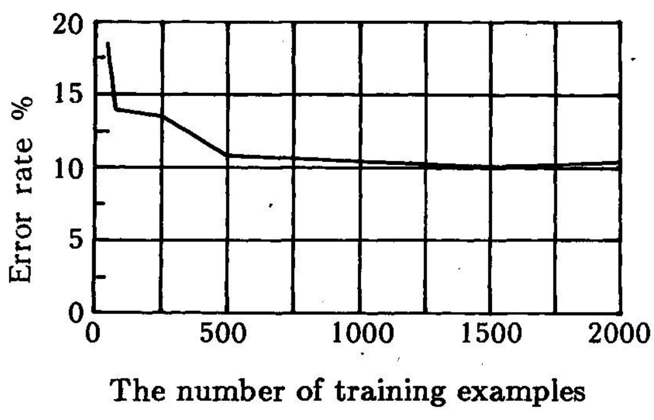


Fig.6 Comparison of the learning results with the number of training examples.

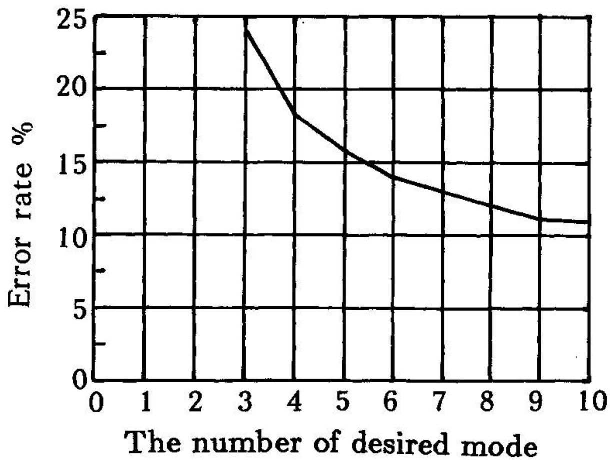


Fig.7 comparison of the learning results with the number of desired mode.

B. Factors of training examples:

(1) The number of training examples

The results show that there is a decreasing monotonical relationship between the number of story of the building and the error rate.

(2) the number of desired mode

The results show that there is a decreasing monotonical relationship between the number of story of the building and the error rate.

5. CONCLUSION

In this paper, artificial neural system is employed to inspect the stiffness loss and the damage location of multistory shear building. Results obtained with various factors of inspected building and various factors of training examples are compared. The results show that the error rate of inspection of stiffness loss and the damage location is dependent on these factors. Therefore, selection of the factors of training examples is an important task in order to minimizing the error rate. However, it can be concluded that an ANS can be sufficiently worked as a tool for damage detection.

Appendix I. Reference

1. Cassaro, M. A. and Romero, E. M. (eds.) (1986). The Mexico Earthquakes-1985, Factors Involved and Lessons Learn, ASCE, New York, N.Y.
2. Stone, W. C. (1986), "Preliminary dynamic analyses of the ministry of agriculture building," in The Mexico Earthquakes-1985, Factors Involved and Lessons Learn, 233-254, Cassaro, M. A. and Romero, E. M. (eds.), ASCE, New York, N.Y.
3. Yao, J. T. P. (1980). "Damage assessment of existing structures," J. of Engineering Mechanics, ASCE, 106(4), 785-799.
4. Ogawa, H., Fu, K. S., and Yao, J.T.P. (1985). "An inexact inference for damage assessment of existing structures," Int. J. Man-Machine Studies, 22, 295-306.
5. Wang, T. Y., Bertero, V. V. and Popov, E. P. (1975) "Hysteretic behavior of reinforced concrete framed walls", Report No. EERC 75-23, Earthquake Engineering Research Center, University of California, Berkeley, California.
6. Hecht-Nielsen, R. (1988). "Neurocomputing: picking the human brain", IEEE Spectrum, March 1988, 36-42.
7. Maren, A. E. (1989), "The need-to-know of neural networks", J. of Neural Network Computing, Summer, 1989, 57-65.
8. McAulay, A. D. (1987). "Engineering design neural networks using split inversion learning", in Proceedings of the First Int. Conf. on Neural Networks, Vol. IV, 635-641, M. Caudhill and C. Butler (eds.), IEEE, San Diego, California, June 21-24, 1987.
9. Rehak D. R., Thewalt, C. R., and Doo, L. B. (1989). "neural network approaches in structural mechanics computations", in Computer Utilization in Structural Engineering, Proceedings of the Sessions at Structures Congress '89, 168-176.
10. Rumelhart, D. E., Hinton, G. E., and Williams, R. J. (1986). "Learning internal representation by error propagation", in Parallel Distributed Processing, Vol. 1, 318-362, Rumelhart, D. E. and McClelland, J. L. (eds.), M.I.T. Press, Cambrideg, MA.

R_j = change rate of the jth story stiffness.

S_i = actual input of the ith input unit.

H_k = output value of the kth hidden unit.

U_j = inference output value of the jth output unit.

T_j = actual output of the jth output unit.

V_{ik} = weight on the link between the ith input unit and the kth hidden unit.

W_{kj} = weight on the link between the kth hidden unit and the jth output unit.

η = learning rate

α = momentum factor

λ_i = ith mode eigen value of the original building

λ_i' = ith mode eigen value of the existing building

Expert System for Maintenance of Timber Warren Trusses
Système expert pour l'entretien de poutres triangulées en bois
Expertensystem für den Unterhalt von Holzfachwerken

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SUMMARY
This paper describes the design and the development of a knowledge-based expert system for the maintenance of timber Warren trusses. These trusses, constructed during World War II, have deteriorated over the years and require repair. In order to properly maintain these buildings, regular inspection by engineers to assess their structural and service conditions is required. A knowledge-based expert system is being developed to aid the engineers, experienced or novice, in conducting an inspection of the trusses. The system integrates the concepts of expert systems, object-oriented programming, relational database and graphics.

RÉSUMÉ
La détérioration due au vieillissement de nombreuses poutres triangulées en bois, du type ferme Warren, construites au cours de la seconde guerre mondiale, exige des travaux de réparation. En vue d'assurer l'entretien convenable des immeubles concernés, les ingénieurs doivent effectuer des inspections régulières des poutres triangulées et déduire leur état d'utilisation. Le système expert élaboré à cet effet doit permettre d'aider les ingénieurs - expérimentés ou novices - dans le déroulement des inspections des éléments porteurs triangulés. Ce système intègre les concepts d'un système expert, une programmation à orientation objet, une banque de données relationnelles et l'infographie.

ZUSAMMENFASSUNG
Im Zweiten Weltkrieg entstanden Holzfachwerke des Warren-Typs, deren Alterung über die Jahre hinweg Instandsetzungsarbeiten erfordert. Für den ordentlichen Unterhalt der betreffenden Gebäude sind regelmässige Inspektionen des Tragwerks und der Nutzungsverhältnisse durch Ingenieure nötig. Das entwickelte Expertensystem soll die Ingenieure - ob erfahren oder nicht - bei der Durchführung der Fachwerkinspektionen unterstützen. Das System integriert die Konzepte von Expertensystem, objektorientierter Programmierung, relationaler Datenbank und Computergraphik.

1. BACKGROUND

1.1 The Structure

The Department of National Defence of Canada (DND) owns many hangar type timber Warren truss buildings on Canadian Forces bases. These buildings, built during and soon after World War II to meet the needs of the expanded Armed Forces establishment, were constructed as temporary structures and were used mainly by the military for aircraft housing and maintenance. Although these buildings were labelled "temporary", it is estimated that there are more than two hundred of them still in service across Canada [1].

Two standardized truss configurations were used in these buildings : an eight-panel pitched chord Warren truss and a seven-panel parallel chord Warren truss, both with a span length of 34.14 m (112 ft). A typical building has eleven trusses spaced at 4.88 m (16 ft). Many of the buildings using the parallel chord truss configuration were constructed with two rows of trusses connected by a line of central columns.

Elevation and plan views of a typical double parallel building are given in Fig. 1. Panel and truss spacings both equal to 4.88 m (16 ft). Although overall configurations of the trusses were standardized using Douglas Fir of selected structural grade, individual details may vary from building to building. Primary variations occurred in the vertical struts and bracing members. The post-tensioning cables as shown in Fig. 1 were not included in the original design and construction. They were installed and used as a strengthening system to release member forces after some members have been found to be subjected to stresses beyond their design strengths.

1.2 The Problem

Because of the large and urgent demand of timber for so many buildings of this size, timber of below specified grade were used for some buildings. Within the first few years of service and after the timber dried out, the trusses began to show signs of distress due to shrinkage. The resulting structural deficiencies included cracking and splitting of truss or splice members, fracture of truss members, excessive deformation and loss of camber. These structural deficiencies were soon recognized and a program of rehabilitation, repair and reinforcement was established. To avoid inconsistent results and to eliminate considerable duplication of effort, DND published the Construction Engineering Technical Order, or CETO [1], which outlined the guidelines and direction for the assessment, repair and maintenance procedures of all DND timber Warren truss buildings.

For the maintenance of these timber Warren truss buildings, CETO recommends that an inspection be performed on these trusses on an annual basis. Condition survey of these timber buildings are usually carried out by military engineers from 1 CEU (1 Construction Engineering Unit). 1 CEU has a limited number of military engineers, most of whom spend about four or more months in the field conducting inspection of timber trusses. It is also DND's policy that military personnel be posted elsewhere every three to four years. This policy leads to a perpetual shortage of experienced engineers who are familiar with the inspection and repair procedures.

Because of the huge inventory of aging buildings and a small number of experienced engineers with the necessary expertise, at times, methods of rehabilitation appear to be more practically available than competent engineers. Extensive consultation is often required to reach an appropriate decision regarding the inspection results as well as the repair solutions.

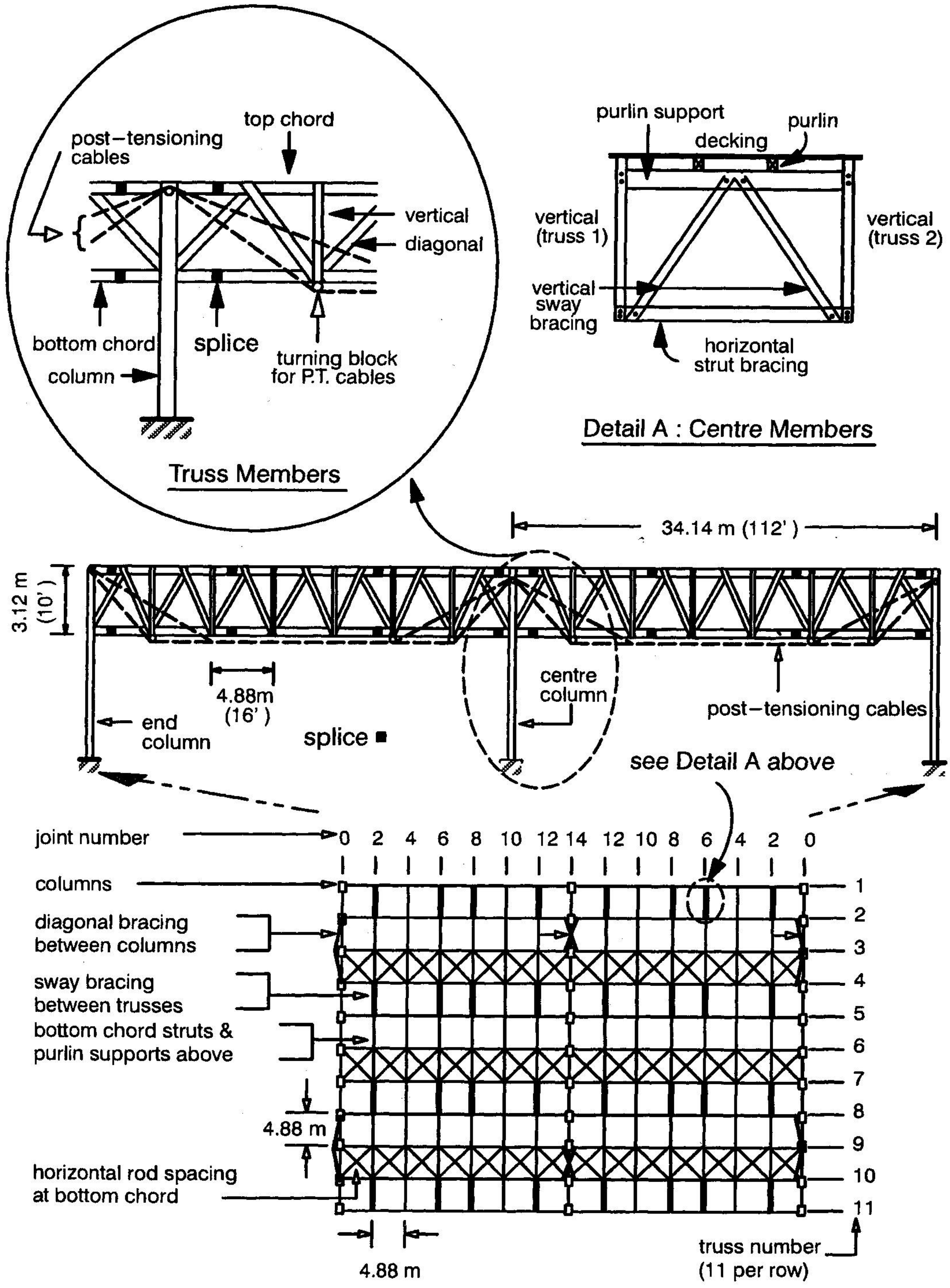


Fig. 1 A double parallel chord Warren truss building

1.3 The Expert System Approach

A method of transferring knowledge from the timber truss inspection experts to less experienced or local inspection personnel is required. An expert system, also known as knowledge-based expert system (KBES), is a computer program which captures human knowledge and decision making processes. Fully developed KBESs are capable of accepting facts from the user, processing these facts against the knowledge base, and on the basis of these facts and knowledge, delivering solutions which are close to the solutions by a human expert.

Primary benefits of using a KBES include reliability (increased possibility of correct and consistent decisions) and productivity (improved efficiency). KBESs can be used as training and education tools for both practising engineers and university students. From the DND's point of view, potential benefits of an expert system application also include the elimination or reduction of such common problems as the lack of trained personnel, the vacuum created during military posting and the time spent in retraining staff.

An object-oriented system is being developed by the KBES group of the Civil Engineering at the Royal Military College of Canada for the overall maintenance of these buildings [2,3]. The system has four knowledge bases : inspection/repair, database management, structural analysis and upgrading of buildings to meet the latest building code. This paper presents the strategies and techniques used in the development of the first two knowledge bases, i.e. inspection/repair and database management. They integrate the concepts of knowledge-base system, object-oriented programming, relational database and hypermedia paradigm in a windowing environment. Illustrative sample sessions are given to demonstrate the capabilities of the system.

2. INSPECTION OF TIMBER WARREN TRUSS

Each truss comprises of truss members, post-tensioning cables and columns as shown in Fig. 1. There are also centre members that exist between neighbouring trusses, including roof deck, purlins and purlin supports. Brief description of the function of each building component is given in CETO.

Typical problems which individual building components may encounter as well as the reinforcing schemes adapted to repair these components are distinctively different from each other. As an example, Fig. 2 lists the possible causes of defect that should be checked when conducting an inspection of a top chord. Appropriate action required to repair these members would depend upon the type of deficiencies that best describe the existing conditions of the member. For example, if split/check found in a top chord is less than 0.5 mm wide, no repair is deemed necessary. If, however, the member has been found to have split/check extended to edge of the member, it needs to be replaced by using the procedures outlined in CETO. Other methods of repair include replacing cracked splice block, installing gusset plates at deteriorated joint and the use of steel shims between top chord and splice connection.

3. OBJECT-ORIENTED EXPERT SYSTEMS

An expert system has two basic components: a knowledge base and an inference engine which is also the control structure of the system. The knowledge obtained from the human expert or experts comprises information specific to the domain of the problem being addressed and is

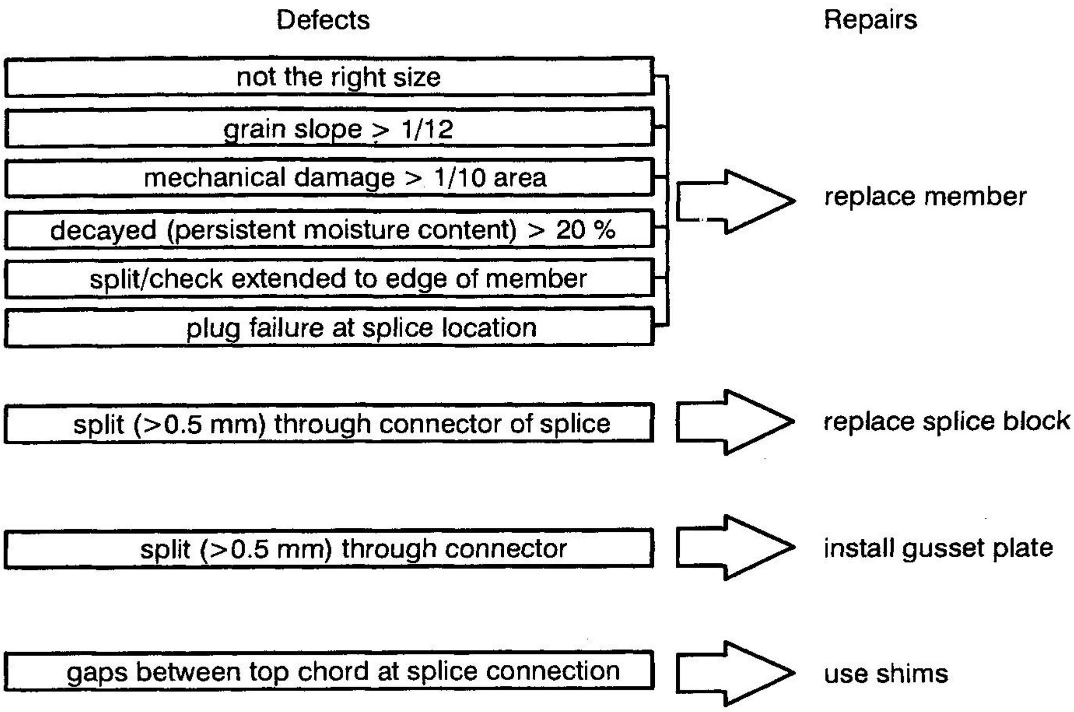


Fig. 2 Inspection consideration for top chord

captured in the knowledge base. The inference engine interprets and applies the knowledge base and attempts to make decisions to problems that would ordinarily require a human expert.

The heart of any expert systems is the knowledge base, which is usually a collection of rules, typically in the form of 'IF...AND..OR...THEN...AND..ELSE..'. If the antecedent of a rule (IF...AND..OR...) is found to be true, the inference engine fires the rule, inferring the 'THEN...AND...' statement(s). There are other components which the knowledge base may be constructed of, such as frames, nets, and more recently object-oriented approach. Because of its modularity, data abstraction and inheritance characteristics, object-oriented programming or OOP, will likely subsume other approaches in the very near future.

In an object-oriented environment, objects represent the properties of a data structure and the operations permitted and performed on the structure. In other words, an object is the sum of its data and procedures and performs operations on itself [4,5,6]. The five key words in OOP are object, class, instance, method and message [7].

A class describes the structure and behaviour of an object within an application and is defined by a collection of characteristics called attributes. An instance is a specific occurrence of an object. Methods are procedures associated with an attribute that can determine the attribute's value or execute a series of procedures when the attribute's value changes. Message is used to invoke operations of an object or among objects. Fig. 3 shows the tree structure of an object used by Level5 Object [4], which is one of the many commercially available software for object-oriented expert system development.

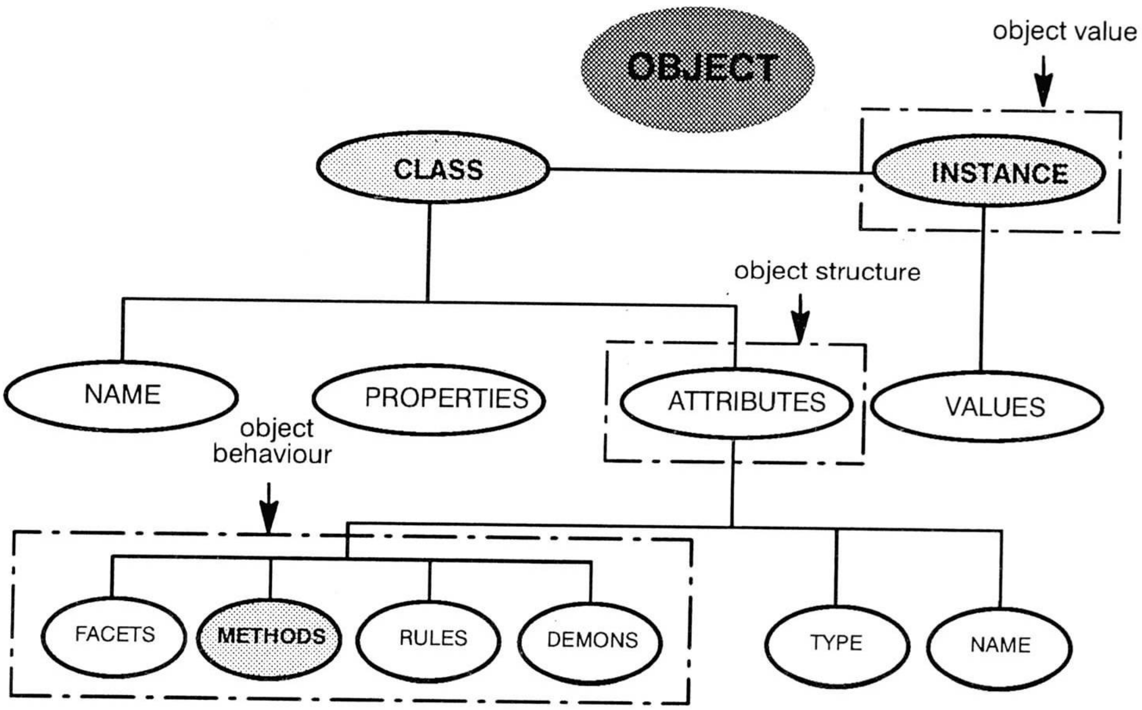
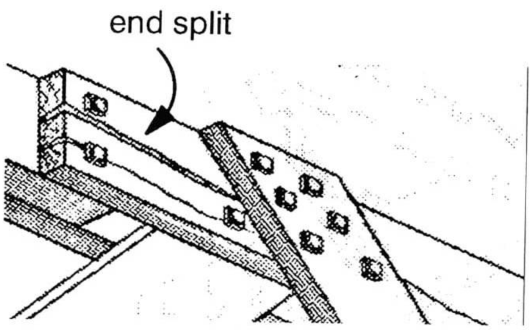


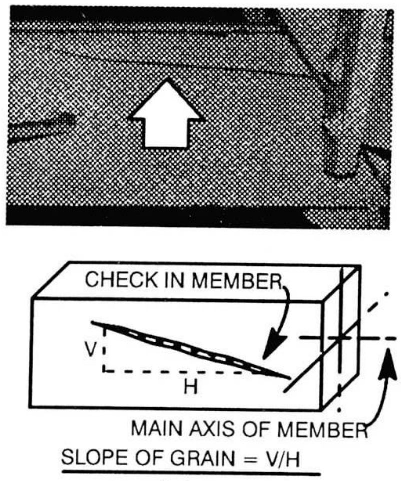
Fig. 3 Defining an object

The object orientation is particular evident in a new class of programming environments that are based on graphical objects rather than text listings. For example, the key feature of the typical information-handling problem encountered during an inspection is the correct interpretation of visual images. To reduce the dependency on subjective judgement and to improve the consistency in decision making, a diagnostic KBES with graphical representation of knowledge is very useful.

An object-oriented system can display implicit knowledge by means of real graphic images as shown in Fig. 4. Fig. 4a depicts an example of an end split. Fig. 4b illustrates an example of split/check and demonstrates how to measure the slope of grain.



(a)



(b)

Fig. 4 Graphical representation of knowledge

4. AN OBJECT-ORIENTED SYSTEM FOR WARREN TRUSS INSPECTION

4.1 System Description

An expert system is being developed for the condition survey of timber Warren trusses. The expert system provides advice to inspectors concerning how to identify deficiencies in the condition evaluation process. The system can also be used as a tutorial for inexperienced inspectors.

The knowledge is drawn mainly from CETO [1] and partially from engineers of 1 CEU. The expert system is being developed on an IBM-compatible personal computer, using an object-oriented shell program [8] in a windowing environment. The system being developed is highly user friendly with many graphics-oriented interface features such as interactive graphics, window management, explanation expansion and graphical representation of knowledge base by mapping graphic displays to and from conclusions.

User help screens are important for both the acceptance and efficient use of KBESs by the user community. They also enhance the use of the system as a training tool. The system has an efficient explanatory component to make the comprehension and checking of how a solution is reached possible and effective. The explanatory facility of the system can be used as an aid for novice engineers to learn, with or without the manuals, more about the inspection process.

User interface plays a major role in the acceptance of any system by its end users. Since the system has graphical user interface with explanatory facilities, little or no programming knowledge and experience is required to use the system. Users simply point and click his/her way through the inspection process to appreciate the dynamic behaviour of the system.

4.2 Example

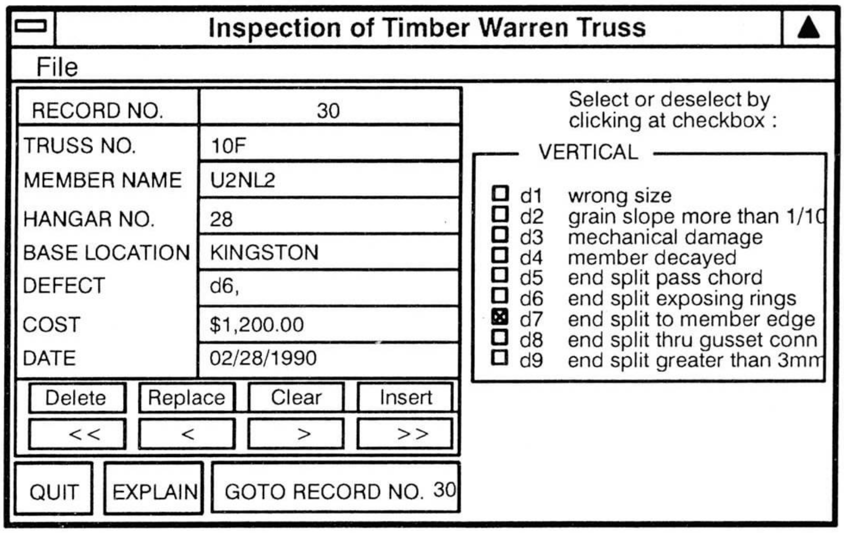
Fig. 5a and 5b illustrate the typical screen images from a sample session when conducting an inspection of a particular truss member. Half of Fig. 5a is devoted to information display and to available database function keys. Member identification and location are drawn from a database. The user can use the database function keys to delete, replace, clear or insert the current record, or to edit the first (<<), previous (<), next (>) or the last (>>) record of the database.

A list of nine (9) possible defects is given in the other half of Fig. 5a in a checkbox form. Clicking on "Explain" pushbutton in Fig. 5a directs the user to an explanatory section as shown in Fig. 5b. The user can learn more about any particular type of defect and the corresponding repair solution, with the aid of photographic images, by selecting the appropriate button in Fig. 5b. Inspection of a member is completed after the user has selected the appropriate checkbox(s) and pressed 'replace' or 'insert' database function key in Fig. 5a.

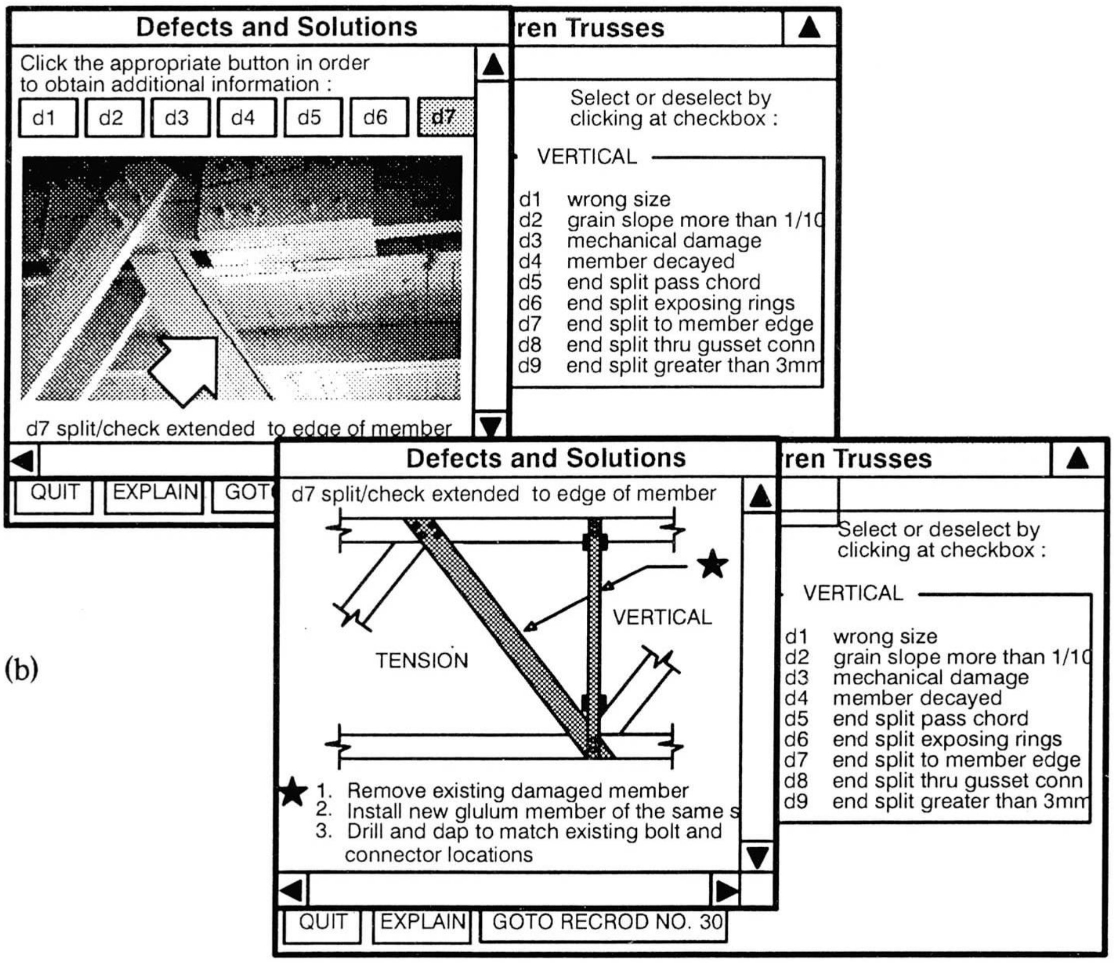
5. AN OBJECT-ORIENTED SYSTEM FOR DATA MANAGEMENT

5.1 System Description

To maintain a huge network of aging buildings, historic data as well as data to be collected from future inspection projects need to be stored and managed properly and effectively. A system is being developed for database management. The system allows direct communication



(a)



(b)

Fig. 5 Typical screen displays of inspection system with external programs and databases, using a management system that integrates and controls the interaction between the knowledge base and the databases. Direct database access enables the system to read and write to files directly from within the knowledge base.

In an object-oriented database management system, data and procedures are coupled. The system views these database entities as objects, which are referenced and manipulated with standard Production Rule Language grammar. Each object combines attributes of procedures and data. The attributes of a class and their attribute types correspond to fields and field types in the external database. Instance of an attribute represents the records in a database.

5.2 Example

Fig. 6a and 6b represent the typical screen images during a consultation session with the database management system. Fig. 6a is the selection display which controls the display and search functions of the system. Depending on the selection option chosen by the user, the system can display data for all records one at time, search and display any record as specified by the user, search and display records related to a particular distress problem, or conduct a relational search. User can specify up to three criteria for the relational search (Fig. 6a). The search shown in Fig. 6b was based on member name and date of the inspection.

(a)

(b)

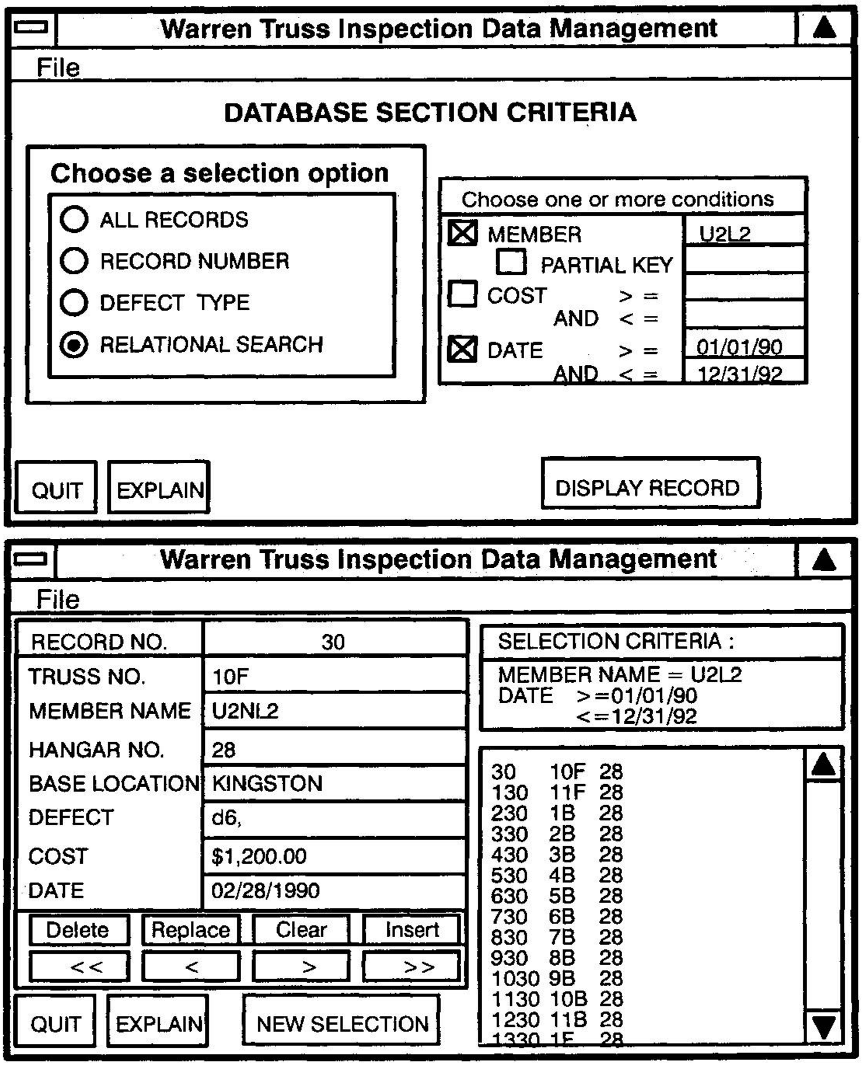


Fig. 6 Typical screen displays for data management system

6. CONCLUSIONS

Expert systems are productivity tools. The availability of sophisticated expert-systems development software for personal computer systems has made the design and development of very complex expert systems possible for engineers who are not computer professionals. Fully developed knowledge-based expert systems can perform certain tasks, such as decision support, design aids and training more effectively and consistently than is possible with current tools and engineering aids.

The development of an object-oriented expert system for the inspection of timber Warren trusses is described. The proposed system integrates the concepts of expert systems, object-oriented programming, relational database and graphics. The system is being developed on and for personal computers. The portable system can be used in the field by inspectors and in the office by management personnel.

7. ACKNOWLEDGES

The financial assistance of the Department of National Defence of Canada is gratefully acknowledged.

8. REFERENCES

1. DEPARTMENT OF NATIONAL DEFENCE OF CANADA, 34 m Warren Type Wood Trusses and Columns Maintenance. Construction Engineering Technical Order, C-98-006/TP-002, National Defence Headquarters, Ottawa, Ontario, 1967 and 1988.

2. FOO H.C. and AKHRAS G., Inspection of DND Warren Truss Buildings Using KBES in a Windowing Environment. Proceedings, Fourth Symposium/Workshop on Applications of Expert Systems in DND, Kingston, Ontario, April 1992.

3. AKHRAS G. and FOO H.C., Timber Truss Inspection Using a Graphical Object-Oriented Expert System. submitted for publication in the Journal of Microcomputers in Civil Engineering.

4. COX B., Object-Oriented Programming : An Evolutionary Approach. Addison-Wesley Publishing Co., Menlo Park, California, 1988.

5. PASCOE G.A., Elements of Object-Oriented Programming. Byte, McGraw Hill, Inc., New York, 1986.

6. TESLER L., Programming Experiences. Byte, McGraw Hill, Inc., New York, 1986.

7. GOLDBERG A. and ROBSON D., Smalltalk-80 : The Language and Its Implementation. Addison-Wesley Publishing Co., Menlo Park, California, 1985.

8. INFORMATION BUILDERS INC., Level5 Object : User's Guide. New York.

A Fuzzy Neural System for Repairing Bridge Decks

Système expert pour déterminer la méthode de réparation des tabliers de pont

Expertensystem zum Bestimmen der Instandsetzungsmethode für Brückenplatten

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SUMMARY

This paper attempts to propose a method that helps maintenance engineers to choose appropriate repairing methods of reinforced concrete bridge decks by using a fuzzy neural expert system. The evaluation measures are lead on damage cause, damage degree and damage propagation speed. One of the important items in the maintenance program is that the present system can provide several appropriate repairing methods by taking account of the past experience through a neural network's learning ability.

RÉSUMÉ

Les auteurs proposent un système expert neuronal à caractère flou comme moyen d'assistance pour les ingénieurs responsables de la maintenance des ponts en béton armé, lors du choix de la méthode de réparation des tabliers. Les critères de sélection se basent sur les causes, l'importance et la vitesse de propagation des dommages. L'une des caractéristiques essentielles de ce programme de maintenance est de pouvoir proposer des méthodes de réparation appropriées qui, grâce à l'aptitude d'apprentissage du réseau neuronal, tiennent compte des expériences passées.

ZUSAMMENFASSUNG

Der Beitrag möchte ein unscharfes neuronales Ingenieurhilfsmittel bei der Wahl geeigneter Instandsetzungsmethoden für Brückenfahrbahnplatten aus Stahlbeton vorschlagen. Die Auswahlkriterien basieren auf Ursache, Umfang und Ausbreitungsgeschwindigkeit des Schadens. Eine wichtige Eigenschaft des Unterhaltsprogrammes ist der Vorschlag mehrerer geeigneter Reparaturmethoden aufgrund früherer Erfahrungen, dank der Lernfähigkeit des neuronalen Netzwerks.

1. INTRODUCTION

In recent years, emphases in the field of civil engineering have drifted from new construction of structures to the maintenance, management and repair of existing structures, and hence maintenance and management work becomes increasingly important. In Japan, due to yearly decline and damage, functional deterioration of bridge structures, especially those built before 1965, becomes a problem. The deterioration and decline of bridges caused by cruel usage due to the changes of Japanese social environment, rapid increase of traffic volume and heavy vehicles, which was not forecasted in construction have become a serious problem. Now it attracts great concern how to plan and carry out maintenance and management of bridge structures.

For above reasons, there are many existing bridges to be repaired or altered[1]. However, it is impossible to rebuild all the damaged bridges because of financial limitation[2]. Evaluation of durability is necessary for appropriate maintenance and repair of bridge structures. Future progress of the damage state of bridge structures should be estimated based on the damage cause, damage degree and damage propagation speed. Then, whether or not a bridge needs to be repaired or rebuilt, and what method should be adopted if repaired, are decided based on the estimation results.

It is difficult to maintain and repair all the bridges because the number of experts engaging in damage assessment cannot satisfy its demand. Therefore, it is very meaningful to build an expert system to help engineers without sufficient experience to make various judgments on maintenance and repair as the expert does[3].

This paper attempts to develop a fuzzy neural expert system for assessing the damage states of RC bridge deck and choosing its appropriate repairing method. The system consists of two subsystems: one is a fuzzy production system for making inferences and the other is a neural network system for deriving solutions. While the fuzzy production system is used to evaluate damage causes, damage degree and damage propagation speed with appropriate knowledge, the neural network system is used to select appropriate repairing methods taking into account of many factors comprehensively. It becomes possible to construct a more practical and useful system by combining these two methods with different characteristics.

2. CONSTRUCTION OF AN EXPERT SYSTEM

2.1 Utilization Environment

The present system has made improvement on the former damage assessment system[4] of RC bridge deck in the following points.

1) The former system was built on an engineering workstation NEWS (made by SONY) with Franz Lisp. In contrast, the present system is built on the same engineering workstation with Common Lisp and C language so that its ability of transplantation and extension is advanced, and it can be used anywhere.
2) In the former system, production rules have been described in Roman alphabet. In contrast, in the present system rules are described in Japanese characters so that expansion, renewal and management of rules become easier for the Japanese user.
3) Data are input in a dialogue form.

2.2 Inference Mechanism

The former system uses forward inference only in fuzzy production system. This system uses forward and backward inference and their combination. By introducing backward inference, inference time of this system becomes shorter. While the former system takes 15-20 minutes from beginning of inference to output of results, the present system reduces inference time up to 1/4.

2.3 Evaluation Method

After an appropriate goal is determined, it is necessary to establish evaluation measures and procedure in order to efficiently support a decision making on maintenance and management. Here, damage cause, damage degree and damage propagation speed are employed as the evaluation measures. It also adopted the learning ability of a neural network to automatically choose repairing methods.

3. ARCHITECTURE OF THE EXPERT SYSTEM

3.1 Fuzzy Production System

The fuzzy production system consists of inference engine including forward and backward inferences, rule base, working memory, fuzzy terms, and fuzzy predicates, as shown in Fig.1.
Both forward and backward inferences can be used in the fuzzy production system by introducing backward inference into the previous system[4].

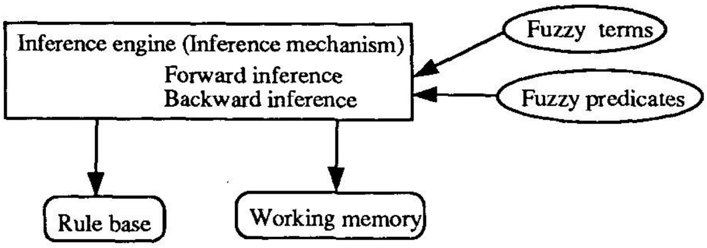

Fig.1 Architecture of Fuzzy Production System

Backward rules for damage causes:

```
(backward-rules
  (r1 ("Damage cause" g-1)  :- (*fc "Damage cause-1"))
  (r2 ("Damage cause" g-2)  :- (*fc "Damage cause-2"))
  ......
  (r16 ("Damage cause" g-16)  :- (*fc "Damage cause-16")))
```

Forward rules for damage causes:

```
(rules "Damage cause-1"
  (rule-1
    if (Crack Form Width-direction)
    then (change-rb "Damage cause-1-1"))
......
  (rule-dummy
    if (*dummy)
    then (change-rb "Result-0-1")))
......
```

where, *fc is a system function executing forward inference

Fig.2 An Example of Rules to Damage Causes Using Forward and Backward Inferences

The system uses a combination of forward and backward inferences to evaluate damage causes of RC bridge deck. Namely forward inference is implemented in the conditional part of backward inference rules. When civil engineers who have the knowledge of maintenance and management of RC bridge deck, want to inquire the results of their subjective judgment based on preliminary survey and inspection, combinational inference of forward and backward inferences can be adopted. Fig.2 shows a part of the rules in the subsystem for evaluating damage causes of RC bridge deck. Fig.2 implies that, for example, when an inquiry such as (?- ("damage cause" g-1)), namely, damage cause of RC bridge deck is [g-1: Extreme wheel load?] is implemented, the system first matches r1 result and the consequent of the backward rule, namely ("damage cause" g-1) is executed, and then moves to forward rules to execute (rules "damage cause-1" ...) using the system function *fc in the conditional part of backward rules (*fc "damage cause-1"). That is, damage cause [g-1: Extreme wheel load?] is investigated in the forward-rules. Here, the forward rules are stored in the form of module. Table 1 presents the possible damage causes of RC bridge deck. Block structure of rules is considered to be an effective method when a large-scale knowledge base is constructed such as the knowledge base for the damage causes of RC bridge deck. When someone wants to know only whether a conclusion can be obtained, the rules only related to damage causes rather than the whole rules in the system need to be investigated using the combination of forward and backward inferences. For example, if the inquiry is successful, the output becomes:

g-1: Extreme wheel load (Truth value: more-or-less-large)

If the inquiry fails, the output is nothing. When an actual expert system is built, it is desirable to decide the assignment of roles of forward and backward and use their combinations according to the knowledge of object.

The advantages of using forward rules in the conditional part of backward rules are as follows[5),6)]:

1) Rules can be described in the form of module because forward rules are to be executed in the conditional part of backward rules.
2) Knowledge can be easily added and modified by describing rules in modules.
3) When someone wants to know only if a conclusion can be obtained, the rules related to such a conclusion rather than the whole rules in the system need to be investigated. In other words, unnecessary search can be avoided to make the system more efficient.

Table 1 Damage Causes

Load	g-1: Extreme wheel load g-2: Impact effect g-3: Inadequacy of girder arrangement
Design and structural factors	g-4: Short of deck depth g-5: Lack of main steel bar g-6: Lack of distribution bar g-7: Inadequacy of distribution cross beam g-8: Additional moment due to differential settlement
Construction conditions	g-9: Poor quality of cement g-10: Poor compaction g-11: Inadequate curing of construction joint g-12: Lack of covering
Other factors	g-13: Salt g-14: Poor drainage g-15: Movement of substructure g-16: Action of alkali material

3.2 Neural Network[7)]

In the system, a subsystem for choosing appropriate repairing methods is constructed by utilizing the learning and pattern recognition abilities of neural network. Fig.3 shows the structure of a neural network.

Learning method: Back-propagation
Combining method: Multi-layer neural network
Input and Output form: Events
Parameters: Synapse weights and threshold values
Input and output function of cell: Sigmoid function

$$f(x)=1/((1+\exp(-x))$$

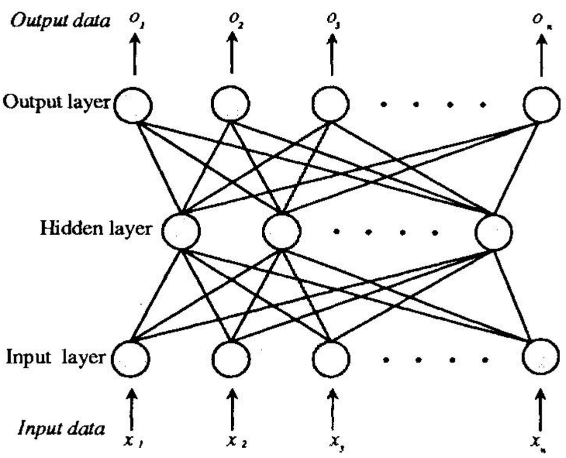

Fig.3 Multi-layer and Back-propagation Neural Network

Introducing the neural network into the expert system, it is possible to consider not only structural factors of RC bridge deck but also economic, construction and environmental factors in choosing the repairing methods.

4. CONSTRUCTION OF THE EXPERT SYSTEM FOR DAMAGE ASSESSMENT OF RC BRIDGE DECK

4.1 Evaluation of Damage Cause, Damage Degree, Damage Propagation Speed by Fuzzy Production System

This system estimates the damage cause from the design condition, environmental condition and inspection data of a bridge, and evaluate the damage degree and damage propagation speed for each cause. The flow chart of the inference process is shown in Fig.4.

Firstly, design and environmental conditions of a bridge are surveyed in advance. Secondly, inspection is carried out at site. Inspection items include crack, pavement, concrete, steel etc. Based on the above survey and inspection results, damage causes yielding the bridge damages are estimated among the causes shown in Table 1. For example, the following rules are used.

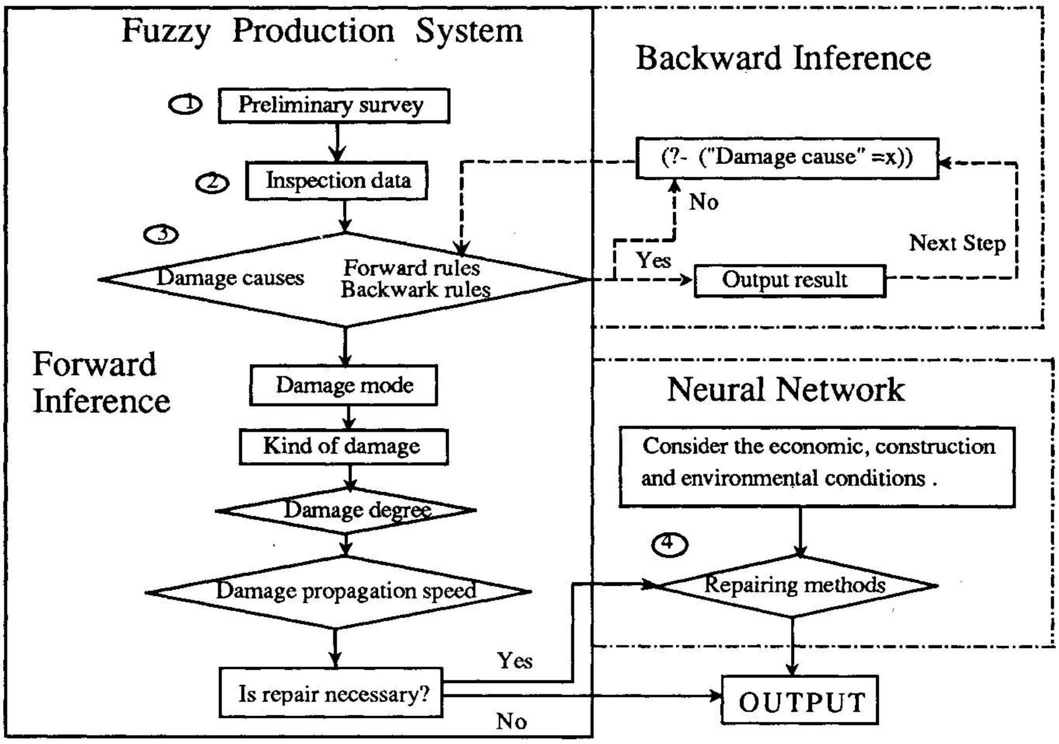

Fig.4 Inference Process of the Expert System

```
(rules "Damage causes-1-2-2"
 very-true
  if    (structural-type plate-girder)
        (crack-configuration  width-direction)
        (crack-location  center-of-deck-span)
        (wheel-load-location  center-of-deck-span)
 then  (deposit ("Damage cause"  Extreme-wheel-load))
        (change-rb  "Damage causes-1-3"))
```

Next, damage modes consisting of only damage types with the same damage causes are established. For example, if a damage cause is assumed to be "Extreme-wheel-load" from inspection results, then the damage mode is made up of damage types concerning crack as shown below.

```
(rules add-mode-1
 (rule-1
  if  ("Damage cause" Extreme-wheel-load)
  then (add (mode crack) 1.0)
       (change-rb add-mode-2))
 (rule mode-1
  (rule-1-1
   if  (mode crack)
   then (change-rb crack-damage-causes-1))
```

Fig.5 An example of membership function for age of RC deck

where, "add" means to add factors into the current working memory.

Next, the type of damages such as crack damage degree, steel damage degree, pavement damage degree, concrete damage degree, structural damage degree etc. are estimated. For example, following rules can be considered to determine crack damage degree:

```
(rules crack-damage-causes-1-1
 (rule-1-1
  true
  if  (crack-form width-direction)
      (crack-width large)
      (crack-space small)
  then (deposit (crack-damage-degree more-large)))
```

In addition to the damage degree and damage propagation speed associated with the damage mode, environmental condition and age of the bridge are considered.

While the former system uses only forward inference to judge damage causes, the present system can use both forward and backward inferences by adding backward inference. Parts of forward rules and rules of combination of forward and backward rules are shown in Fig.2. Some membership functions used in the system are shown in Fig.5.

4.2 Automatic Selection of Repairing Methods by Neural Network

As shown in Fig.4, the system first evaluates damage cause, damage degree and damage propagation speed by the fuzzy production system. Then, suitable repairing methods are chosen through the learning ability of neural network by taking into account of the effects of importance, economy and construction condition of bridges.

The architecture of the system for choosing automatically repairing methods by neural network is illustrated as follows:

1) As stated in previously, inference results obtained from the fuzzy production system, namely, damage cause, damage degree, damage propagation speed of RC bridge deck, are used as input data. In addition, structural property, economic, construction and social effects etc. are taken into account together. Here the results obtained from the fuzzy production system are represented in the form of fuzzy set.
2) A four-layered neural network is used.

First layer (input layer): In the input layer, fuzzy data are represented as a fuzzy unit group and non-fuzzy data as a crisp unit group.
Second layer: 20 unit
Third layer: 20 unit
Fourth layer (output layer): Adding stringer method, retrofitting method by steel plate deck and rebuilding method are considered as representative repairing methods, and denoted as A, B, C respectively. As an example, when the output is B, it is represented as:
(A, B, C)=(0, 1, 0)

3) The input data are learned.
4) In order to evaluate the learning accuracy, it is necessary to achieve some criteria for the correctness of identification. In this study, it is thought that a highly precise diagnosis has been made if the result obtained from the neural network is nearly consistent with actual records.

5. NUMERICAL EXAMPLES

The applicability and usefulness of the present system is demonstrated by using actual data in the durability assessment of RC bridge deck. Numerical experiments on the selection of repairing methods are carried out using both the fuzzy production system and neural network. The data are collected from the actual repairing records made past for 13 bridge in Osaka City, Japan.

5.1 Reasoning by Fuzzy Production System

The input of data such as structural type, inspection results, environmental condition, etc. are implemented interactively as shown in Fig.6. Here, the following rules (about 700 rules) are used:

1. Rules for damage reasoning	31
2. Rules for estimating damage causes	223
3. Rules for damage mode	5
4. Rules for evaluation of crack damage degree	55
5. Rules for evaluation of road pavement damage degree	37
6. Rules for evaluation of reinforcing steel damage degree	4
7. Rules for evaluation of concrete damage degree	20
8. Rules for evaluation of structural damage degree	20
9. Rules for judgment of comprehensive damage degree	187
10.Rules for judgment of damage propagation speed	28
11.Rules for selection of repairing method	31
12.Rules for output of results	51

First, the data obtained from preliminary survey and inspection are input. For example, Table 2 and Table 3 present the design conditions, environmental conditions, and inspection data of a RC bridge deck. Using these data, working memory is rewritten as shown in Fig.7. For instance, the working memory concerning the age of the RC bridge deck is rewritten as follows:

```
> <Input of Data>
  1. Construction of data file
  2. Load existing data file
    => 1
  Curve bridge?
  y: yes
  n: no
    => y
 Degree of truth value?
 1. truth
 2. absolute-true
 3. more-true
 4. true
 5. more-or-less-true
 6. fairly-true
 x. other
   =>1
a. Add input data?
 re: renew the input data from first
 sp: stop
 except keyboard: next input
   =>3
Structural type of bridge?
 1. plate girder
 2. box girder
 3. arch (below road)
 4. arch (upper road)
 x. other
   =>3
......
Write above data into file?
y: yes
n: no
   => y
Input file name => file.1
Make another file?
 1. Make another file
 2. Implement the inference
   => 2
Inference results:
......
```

Fig.6 Interactive input

Table 2 Design and Environmental Conditions

Kind	Factor	Data	Truth value
Design conditions	Structural type	Plate girder(straight)	1
	Design specification	Before 1967	1
	Construction year	Old	very-true
	Deck thick	20cm	1
	Bridge length	69.00m	1
	Bridge width	12.95m	1
	Lanes	3 lanes	1
	Foot way	One side	1
Environmental conditions	Erection location	Near city	1
	Road rank	Main road	1
	Ratio of heavy vehicle	Many	very-true
	Traffic flow	Many	very-true
	Wheel load location	Center of deck span	absolute-true

Table 3 Inspection Data

Kind	Factor	State	Truth value
Crack	Configuration	Width direction	absolute-true
	Location	Center of deck span	very-true
	Density	6.63	1
	Space	Large	very-true
	Width	Large	very-true
Road surface	Pavement	Large uneven	very-true
		Small log	true
Concrete	Color change	Medium	true
	Oldness	Medium	true
	Alienation lime	Center of deck span	absolute-true
Steel	State of rust	Rusting	absolute-true
Other	water around	Medium	true
	Leaking water	Center of deck span	very-true

very-true/(deck age medium)

Next, forward inference is commenced using inference rules and the rewritten working memory. The results shown in Table 4 can be obtained after about two minutes inference. Here, truth value is expressed in linguistic forms.

If one wants to know whether some damage cause exists, forward inference can be used in the antecedent part of backward rules when judging damage causes of RC bridge deck in the system. In this case, matching is implemented between inquiry content and consequent part of backward rules to investigate if the antecedent condition of rules is satisfied. As an example, provided that an inquiry whether or not

```
(working-memory
 {      (structural-type girder-plate),
        (design-specification 1967),
   very-true/(construction-year old),
        (deck thick 20),
        (bridge-length 69),
        (bridge-width 12.95),
        (lanes 3),
        (foot-way one-side),
        (erection-location near-city),
        (road-rank main-road),
 absolute-true/(location-of-wheel-load center-of-deck-span),
   very-true/(rate-of-heavy-vehicle many),
   very-true/(triffic-flow many),
 absolute-true/(crack-configuration width-direction),
   very-true/(crack-location center-of-deck-span),
        (crack-density 6.63),
   very-true/(crack-space large),
     true/(crack-width w-large),
   very-true/(road-pavement uneven),
     true/(road-pavement small-log),
     true/(concrete-color-change medium),
     true/(concrete-oldness medium),
 absolute-true/(concrete-alienation-lime center-of-deck-span),
 absolute-true/(steel rusting),
     true/(water-around medium),
   very-true/(leaking-water center-of-deck-span),
})
```

Fig.7 An Example of Working Memory

the damage cause is [g-1: Extreme wheel load], the following inference result is obtained:

>(?- ("Damage causes" g-1))
[Inference Result]
g-1: Extreme wheel load (Truth value: more-large)

Table 4 Inference Results

Damage causes (Truth value)	g-1:	Extreme wheel load	(more-large)
	g-6:	Lack of distribution bar	(small)
	g-15:	Poor drainage	(large)
Damage degree (Truth value)	g-1:	more-large	(small)
	g-6:	more-large	(small)
	g-15:	large	(more-large)
Damage propagation speed (Truth value)	g-1:	more-large	(more-large)
	g-6:	medium	(small)
	g-15:	more-large	(large)

5.2 Selection of Repairing Methods by Neural Network

Because the above inference results are given by fuzzy sets to deal with the inference results and take into account of the effects of importance, economy and construction condition of bridges in a unified manner, the data containing fuzziness are expressed by fuzzy unit groups and the data not containing fuzziness are expressed by crisp unit groups. For example, it is defined that [crack damage is small]={1/0, 0.66/1, 0.33/2, 0/3, 0/4, 0/5, 0/6, 0/7, 0/8, 0/9, 0/10}. As a fuzzy unit group, [crack damage is small]={1, 0.66, 0.33, 0, 0, 0, 0, 0, 0, 0, 0} are input to 11 units of the input layer in the neural network, whereas the data not containing fuzziness are represented by binary values as a crisp group. For example, it is 1 when steel reinforcing bars are exposed and 0 otherwise. The output of results is A or B or C, where A denotes the repairing method by additional stringers, B the retrofitting method by steel plate deck and C rebuilding method. For example, when the output is B, it can be expressed as (A, B, C)=(0, 1, 0). Then, through the neural computation, it is possible to judge which repairing method is suitable for this case. The output values for bridge No.1 are A=0.94, B=0.05, C=0.04. Thus A should be chosen as repairing method. It can be seen that the outputs agree completely with the past record, and hence the learning has been carried out precisely.

6. CONCLUSIONS

Appropriate damage assessment is important in maintenance program of bridge structures. This research has developed a practical expert system for damage assessment of bridge structures, based on the knowledge of experts who make various judgments efficiently in daily maintenance and management work. The durability of RC bridge deck is considered as a main evaluation object in the system. Based on the damage cause, damage degree and damage propagation speed, repairing method can be chosen automatically. By introducing the fuzzy logic into the system, it becomes possible to deal with linguistic data given by the subjective judgments of engineers[8]. Practical and useful solutions can also be obtained even from incomplete data. Furthermore, repairing methods can be chosen automatically, while considering a lot of factors by introducing a neural network into the expert system.

The characteristics of the present expert system for damage assessment of RC bridge deck can be summarized as follows:

1) Since the system was built on a 32 bit engineering workstation NEWS (made by SONY) and written in Common Lisp and C language, anyone can use it at any time and place without difficulty.
2) Using this system, it is possible to evaluate a lot of bridges with relatively short time.
3) Inference time can be reduced by module of rules. While the former system takes 15-20 minutes from beginning of inference to output of results, the present system reduces up to 1/4.
4) Because data can be input in a dialogue form, anyone can use it without difficulty.
5) Because backward inference can be implemented in the system, both forward and backward inference can be used in the fuzzy production system. Implementing forward rules in the antecedent part of backward rules, it is possible to reduce the inference time.
6) It becomes clear from this study that, in order to solve efficiently a practical problem, appropriate results can be obtained by using fuzzy production system when knowledge is easily attainable, or relationships between events are clear. However, when it is difficult to make out rules, meaningful results can be obtained by utilizing the learning ability of neural network[9)-12)].

REFERENCES

1. N. Shiraishi, H. Furuta and M. Sugimoto : Integrity Assessment of Bridge Structures Based on Extended Multi-Criteria Analysis, Proc. of ICOSSAR, Vol. 1, pp.505-509, 1985.
2. K. Komai, N. Kimata and T. Kobori : A Fundamental Study on Evaluating System of Bridges for Maintenance and Control Planning, Proc. of Japan Society of Civil Engineers, Vol.428/I-15, pp. 137-146, 1991. (in Japanese)
3. N. Shiraishi, H. Furuta, M. Umano and K. Kawakami : An Expert System for Damage Assessment of a Reinforced Concrete Bridge Deck, Fuzzy Sets and Systems, Vol.44, pp.449-457, 1991.
4. H. Furuta, N. Shiraishi, M. Umano and K. Kawakami : Knowledge-based Expert System for Damage Assessment Based on Fuzzy Reasoning, Computer and Structures, Vol.40, No.1, pp.137-142, 1991.
5. M. Umano : Fuzzy Set Manipulation System in Lisp, Proc. of 3rd Fuzzy System Symposium, pp.167-172, 1987. (in Japanese)
6. T. Nakajima : Realization of Backward Inference and Its Combination with Fuzzy Data Based on Fuzzy Production System, Master Thesis, Kansai University, 1991. (in Japanese)
7. Y. Hayashi and A. Imura : A Neural Expert System Using Fuzzy Teaching Input, Proc. of 6th Fuzzy System Symposium, pp.49-55, 1990. (in Japanese)
8. H. Furuta : Fuzzy Expert System, System/Control/Information, Vol.34, pp.288-294, 1990. (in Japanese)
9. H. Furuta, M. Umano, K.Kawakami, H. Ohtani and N. Shiraishi: A Fuzzy Expert System for Durability Assessment of Bridge Decks, Proc. of ISUMA, pp.522-527, 1990.
10. A. Miyamoto, H. Kimura and A. Nishimura : Expert System for Maintenance and Rehabilitation of Concrete Bridges, Proc. of IABSE Colloquium on Expert System in Civil Engineering, pp.207-217, 1989.
11. I. Mikami, S. Tanaka, A. Kurachi and S. Yoneda : Inference by Analogy and Negative Learning for Selecting Retrofitting Method of Steel Bridge Fatigue Damage, Journal of Structural Engineering, Vol.38A, pp.557-570, 1992. (in Japanese)
12. A. Miyamoto, H. Morikawa and M. Kushida : Engineering Dealing of Subjective Uncertainty in Bridge Rating, Proc. of ISUMA, pp.539-545, 1990.

Bridge Management: A Knowledge Based Expert System Approach

Approche d'un système expert pour la gestion des ponts

Ein Expertensystemansatz für die Brückenverwaltung

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SUMMARY
This paper presents a comprehensive microcomputer based bridge analysis and rating system. The system incorporates the grillage analogy method as the analysis medium, the American Association of State Highway and Transportation Officials (AASHTO) load factor of resistance method of bridge rating. The use of expert system technology in Bridge rating has been explored in this paper.

RÉSUMÉ
Cet article présente un système informatique exhaustif destiné aux calculs de vérification et à la classification des ponts. Ce système comporte la méthode analogique en grille servant d'instrument de calcul, les hypothèses de charge d'après les règlements AASHTO et la méthode de résistance pour classer les ponts. Ce système a ainsi servi à vérifier la possibilité d'utiliser un système expert comme principe de classification des ponts.

ZUSAMMENFASSUNG
Der Beitrag stellt ein umfassendes Mikrocomputersystem für die Nachrechnung und Einstufung von Brücken vor. Das System enthält das Trägerrostverfahren als Recheninstrument, die Lastannahmen nach AASHTO-Vorschrift und die Widerstandsmethode zur Brückeneinstufung. Damit konnte die Einsatzmöglichkeit eines Expertensystems in der Brückenklassierung untersucht werden.

1. BRIDGE MANAGEMENT

Of the over half million highway bridges in the United States, 42% are classified as structurally or functionally deficient and 75% are over 50 years design life. Several factors are attributed to this, including increased live loading, conservative design, deferred maintenance and repairs, etc. These factors lead to an increased role of bridge management, which must relate to safety as well as economy. Insuring bridge safety requires a balance between the loads imposed on a bridge and the capacity of its members. The development of bridge evaluation considering the structural safety of the bridge and the safety of its users is an essential component of bridge management involving decisions on new bridge designs, closing or rating of existing bridges.

AASHTO recommends the use of higher levels of analysis (finite elements, finite difference, semicontinuum, grillage, etc.) and rating to reevaluate bridges found to be deficient. The system should take into account the states of deterioration and distress, and effort expended on inspection, evaluation, and maintenance.

The following load and resistance factor equation is used to determine the load carrying capacity:

$$RF = \frac{\phi R_n - \gamma_D D}{\gamma_L L(1 + I)}$$

where
RF = rating factor (the fraction of the rating vehicle loading allowed on the bridge),
R_n = nominal resistance of the bridge,
ϕ = capacity reduction factor,
γ_D = dead load factor,
D = dead load effect,
γ_L = live load factor,
L = live load effect, and
I = impact factor.

Live load modeling is a complex aspect of the ultimate load capacity evaluation of the bridges. Important parameters in the live load model were identified which included truck configuration (truck type, axle spacing, and axle percentage of weight distribution), gross truck weight, multiple presence of trucks on the bridge, and impact which is dependent on the roadway roughness. Impact factors based on physical tests and weigh-in-motion measurement of bridges under normal traffic were reviewed and then incorporated into the knowledge domain. The maximum live load effect is usually caused by the multiple occurrences of trucks on the bridge, i.e., same lane occupancy effects. Appropriate values of the multiple truck presence factor were incorporated. Improved realistic values of the factors for the resistance, dead load and live load effects were determined based on the constructed representative knowledge domain. The resistance and live load factors also depend on the level of maintenance and inspection, the use of field measurements to estimate the girder distribution factors and the number of lanes of the bridge [1-3].

2. ANALYSIS

The grillage analogy was for analysing the bridges. It is an economical and simple method that can be fully automated using a microcomputer [4-6]. Results from the grillage analysis as applied to bridge structures is well supported by published literature [7-12], among which are Lightfoot [1964], Sowka [1967], West [1973], Hambly [1976], Cope and Clark [1984], and Bakht and Jaeger [1986]. The grillage program used in the development of the system is called BRIDGES [13].

3. EXPERT SYSTEM DEVELOPMENT

Advanced computer applications have made the practice of structural engineering much more efficient in recent years. The use of expert system technology was explored with respect to load factor selection, quantifying the bridge condition, and rating factor interpretation [14]. The *Exsys Professional* [15] shell was used in the development of the expert system ***REX*** **[RatingEXpert]**.

A modular design approach was adopted for the development of the expert system. This method made the appropriation of tasks more lucid and would facilitate further enhancements. Figures 1, 2, and 3 illustrate detailed flow charts of the three system modules showing the interaction between external programs and the knowledge base.

The system first queries for information necessary to determine values for the factors, ϕ, γ_D, γ_L, and I in the rating equation. The value of ϕ is dependent on superstructure condition, redundancy, type of maintenance and inspection, and type of steel [1,3]. The value of γ_D takes into account the accuracy of the assumed weight of the structure. The value of γ_L reflects the likelihood of extreme loads side-by-side and following in the same lane and the possibility of overloaded vehicles. The value of the impact factor, I, is calibrated according the roadway surface condition [1,2]. According to AASHTO, γ_D and γ_L, should be selected from categories which were determined from weigh-in-motion studies and structural reliability methods. This information is stored in the knowledge base.

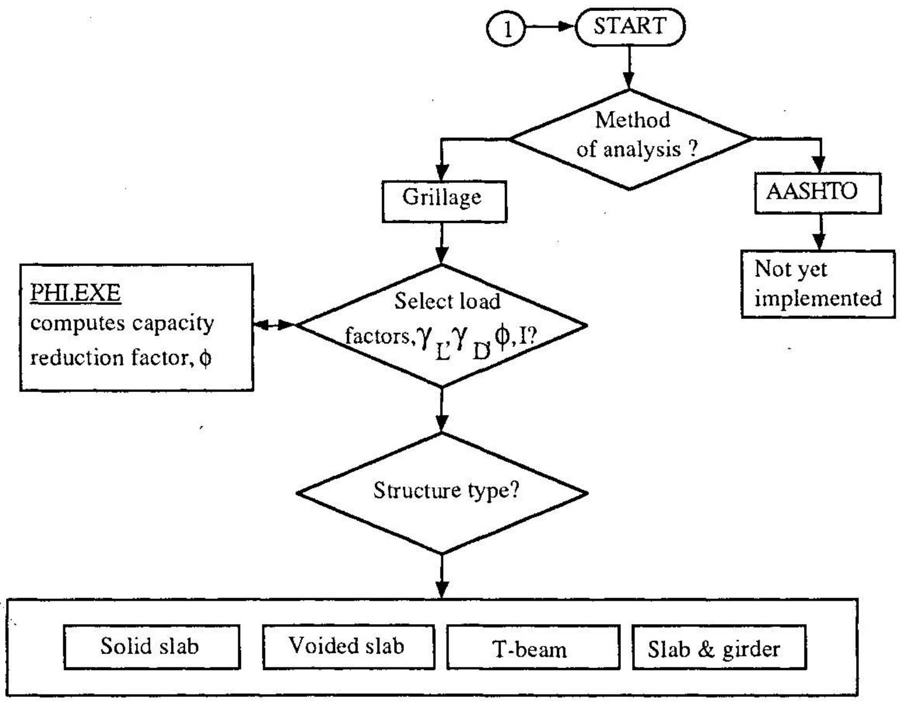

Fig. 1. Load factor selection module

After the load factor selection is complete a series of external programs are executed to generate the input for the grillage program and determine the responses. Depending on the bridge type, the user will be asked questions regarding the geometric properties particular to that bridge cross section type. Cross-sectional properties of standard cross sections are stored in a database. The system creates the grillage mesh and input in a format legible to the grillage program, BRIDGES. The idealization follows the suggestions of Bakht and Jaeger [4-6].

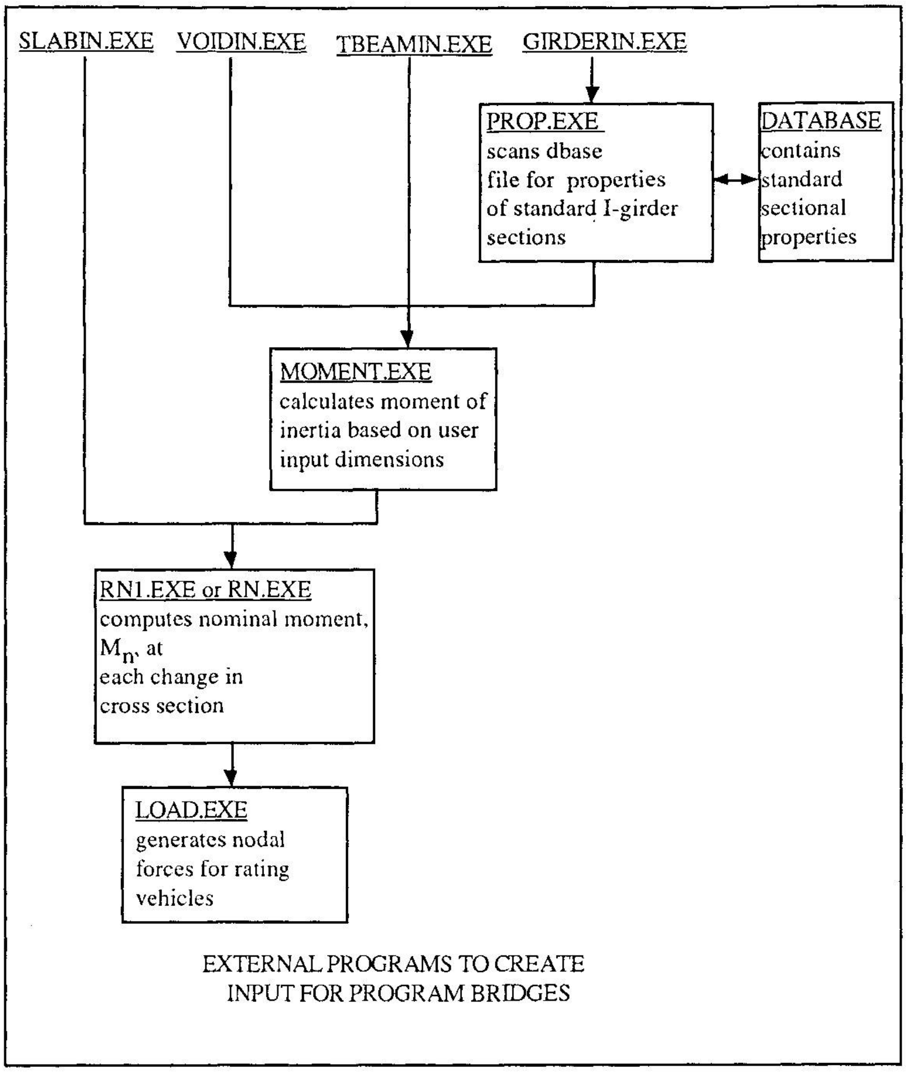

Fig. 2 Input generation module

The knowledge base has 24 built in live load configurations plus a custom load creation option. The built-in loadings include traditional AASHTO truck and lane loading configurations, current AASHTO truck configurations, and Florida truck configurations.

The program BRIDGES is executed and the maximum value of L and corresponding value of D are obtained for each span to span beam. At each variation in the transverse cross section (i.e. edge beams, sidewalks, etc.) the user is asked to provide the steel properties and the system computes the values of the resisting moment, R_n, based on AASHTO/ACI provisions [16-19]. The system then computes the rating factor for each group of grillage beams corresponding to a span to span beam on the bridge and the governing critical rating is then determined from among the rating factors.

The output of the system consists of two parts: the *Exsys Professional* output and the detailed output file. The *Exsys Professional* output contains the resistance and load factors used, the maximum moments, the governing rating factor, and an interpretation of the result. The detailed output file is more comprehensive and contains an echo of the input, a plot of the mesh, deflections at each node, the rating factors for each beam, and the governing rating factor.

4. SCOPE

The current system is capable of analyzing and evaluating simply supported solid and voided slabs, AASHTO girder and slab, and T-beam bridges [Figure 4]. The system also accommodates the presence of edge-stiffening such as sidewalks, edge beams, and parapets and additional overlays such as asphalt and concrete.

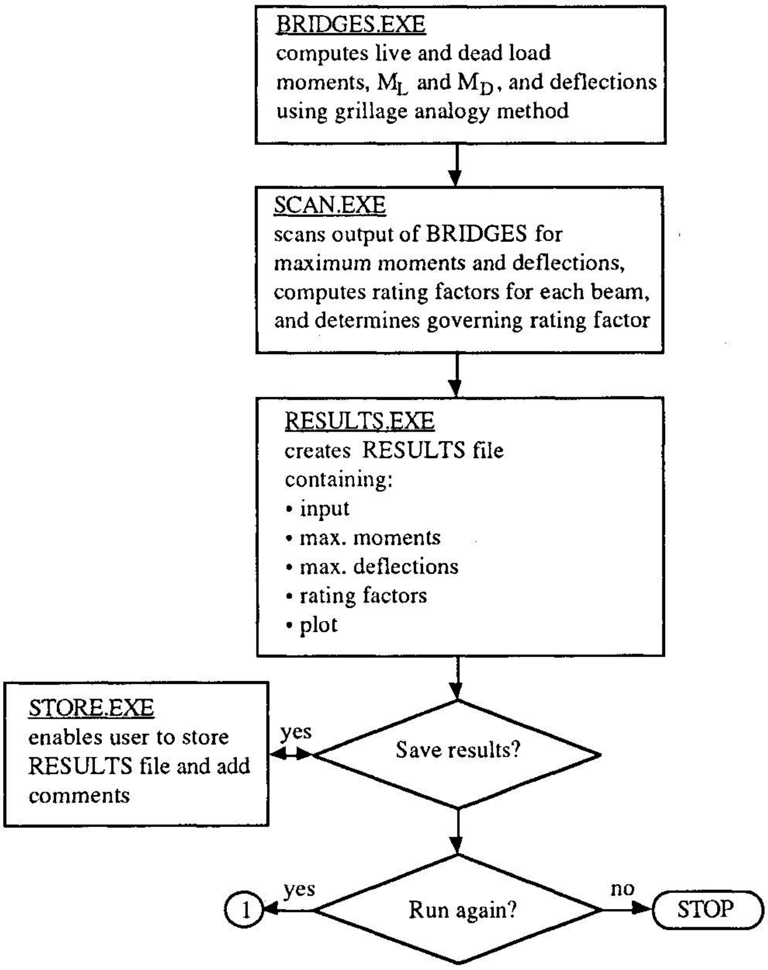

Fig. 3 Computation and results module

5. APPLICATION TO ACTUAL BRIDGE [20]

The rating results of the expert system were compared to actual field tests conducted on bridges maintained by FDOT to determine the effectiveness of the system. Figure 5 shows a portion of the output file produced by the expert system for bridge # 780021 in St. Johns County, Florida. The bridge is a solid slab bridge with edge beams and has a width of 34 feet (10.36m) and a span of 20 feet (6.10m).

The rating factor for an SU2 (34 kips; 151.24kN) rating vehicle is determined to be 2.45. This was established by the FDOT on February 26, 1992 based on incremental loading and strain measurements. The operating rating factor determined using the expert system is 2.32.

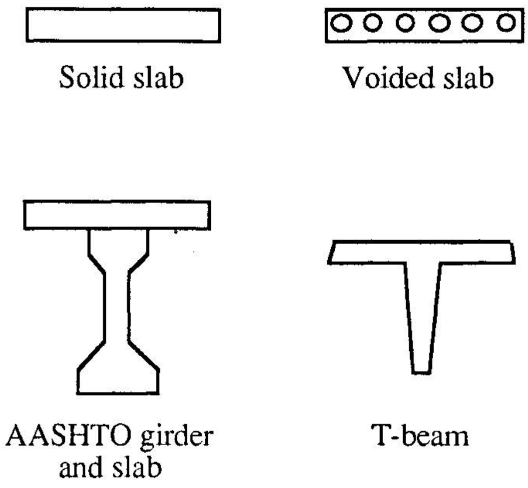

Fig. 4 Types of bridge cross-sections that are incorporated in the expert system

CRITICAL RATING FACTOR

RATING FACTOR = 2.32
NOMINAL MOMENT, Rn(kip-ft) = 61.59
DEAD LOAD MOMENT, MD, (kip-ft) = 6.63
LIVE LOAD MOMENT, ML, (kip-ft) = 8.08

1 kip-ft = 1.356 kN-m

LOAD AND RESISTANCE FACTORS

Φ = 0.80
γ_L = 1.67
γ_D = 1.3
Impact Factor, I = 1.3

	RATING FACTOR	Rn (kip-ft)	ML (kip-ft)	MD (kip-ft)
BEAM 1	3.40	177.89	14.05	29.66
BEAM 2	5.38	61.59	3.58	5.76
BEAM 3	4.16	61.59	4.59	5.99
BEAM 4	3.04	61.59	6.23	6.28
BEAM 5	2.70	61.59	6.97	6.51
BEAM 6	2.32	61.59	8.08	6.63
BEAM 7	2.32	61.59	8.08	6.63
BEAM 8	2.70	61.59	6.97	6.51
BEAM 9	3.04	61.59	6.23	6.28
BEAM 10	4.16	61.59	4.59	5.99
BEAM 11	5.38	61.59	3.58	5.76
BEAM 12	3.40	177.89	14.05	29.65

Fig. 5. Partial output listing showing rating results

6. RESULTS AND CONCLUSIONS

The expert system developed in this project succeeded in providing a prototype model [21]. It provides an interface between the user and complex computer analysis programs via an expert system shell and various other conventional programs. The system is designed to be user-friendly and requires minimal computer knowledge; it is entirely menu driven and easily operable. It enables the novice, with little knowledge of bridge engineering, to analyze and evaluate the load carrying capacity of a highway bridge successfully. The tedious and mistake prone task of bridge idealization and calculation of the corresponding section properties has been automated. Mundane tasks such as the processing of large outputs and calculation of the rating factors are now performed by the computer.

The rating factors provided by the system for the four bridge types have been validated with rating factors obtained by actual field tests conducted by the FDOT.

The database containing a wide array of data pertaining to six standard cross sections is being updated with additional cross sections such as standard T-beams, cellular decks, etc. The knowledge base can be readily accessed and modified as bridge codes and expertise change and as more bridge types are added to the system. Selection of load and resistance factors based on structural reliability methods eliminated the need to evaluate a bridge based on two rating levels, inventory and operating [1]. Furthermore, utilizing the grillage analogy method eliminated the need for distribution factors in determining the live load effect.

Current work to create a more comprehensive system include: a rating for shear, a graphical input, a complete library of standard cross sections stored in the database and more emphasis on the bridge condition and load factor selection through the use of fuzzy logic is being explored [22].

ACKNOWLEDGEMENTS

The first three authors would like to thank Dr. S. E. Dunn, Chairman, Department of Ocean Engineering and Dr. C. S. Hartley, Dean, College of Engineering, Florida Atlantic University for their encouragement and support in preparation of the paper. This paper is based on a project entitled "Knowledge Based Expert System for Rating Florida Bridges" funded by the Florida Department of Transportation.

REFERENCES

1. Transportation Research Board, Load Capacity Evaluation of Existing Bridges, NCHRP Report No. 301, Washington, D.C., December, 1987.

2. Transportation Research Board, Strength Evaluation of Existing Reinforced Concrete Bridges, NCHRP Report No. 292, Washington, D.C., June, 1987.

3. AASHTO, Guide Specifications for Strength Evaluation of Existing Steel Concrete Bridges, Washington, D.C., 1989.

4. BAKHT, B., JAEGER, L. G., Bridge Analysis Simplified, McGraw-Hill Book Company, 1985.

5. JAEGER, L.G., BAKHT, B., Bridge Analysis by Microcomputer, McGraw Hill Book Company, 1989.

6. JAEGER, L.G. , BAKHT, B., The Grillage Analogy in Bridge Analysis, Canadian Journal of Civil Engineering, 9(2), 1982 pp 224-235.

7. LIGHTFOOT,E., "A Grid Framework Analogy of Laterally Loaded Plates", International Journal of Mechanical Sciences, Pergamon Press, Oxford, England, Vol.6, June, 1964.

8. SAWKO, F, "Computer Analysis of Grillage Curved in Plan", Publ. IABSE, Vol. 27, Inst. Association of Bridge and Structural Engineers, Zurich, 1967.

9. WEST, R., Recommendations on the Use of Grillage Analysis for Slabs and Pseudo-slab Bridge Decks, Report 46.017, Cement and Concrete Association, and Construction Industry Research and Information Association, London, 1973.

10. HAMBLY, E.C., Bridge Deck Behavior, Chapman and Hill, London, 1976.

11. COPE, R.J., CLARK, L.A., Concrete Slabs : Analysis and Design, Elsevier Applied Science Publishers, 1984.

12. BAKHT, B., JAEGER, L.G., Analysis of Bridges with Intermediate Supports by the Semi-continuum Method, Proc. Annual Conference of the Canadian Society for Civil Engineering, Toronto, 1986.

13. SEN, R., Bridges: A Computer Program for the Grillage Analysis of Bridge Decks According to AASHTO Loading, December, 1987.

14. AROCKIASAMY, M., Expert System Applications to Structural, Transportation, and Environmental Engineering, CRC Press, 1992.

15. Exsys Professional, EXSYS System Development Package, 1988.

16. AASHTO, Standard Specifications for Highway Bridges, 14th edition. Washington, D.C. (1989).

17. ACI, Building Code Requirements for Reinforced Concrete (ACI 318-89), Detroit, Michigan, November, 1989.

18. NAWY, E.G., Prestressed Concrete: A Fundamental Approach, Prentice-Hall Inc., 1989.

19. NAWY, E.G., Reinforced Concrete: A Fundamental Approach, Second Edition, Prentice-Hall Inc., 1990.

20. SAWKA, M., Knowledge Based Expert System for the Analysis and Rating of Florida Bridges, Masters Thesis, Florida Atlantic University, 1992.

21. AROCKIASAMY, M., SAWKA, M.J., SINHA, V., SHAHAWY, M. A., Knowledge Based Expert System Approach for Analysis and Rating of Florida Bridges, Proc. Second International Conference on Bridge Management, University of Surrey, U.K., April 18-21, 1993.

22. SINHA, V., Knowledge and Fuzzy Logic Based Bridge Management Decision System, Unpublished Doctoral Dissertation Proposal, Florida Atlantic University, 1992.

Intelligent Methodological Support of Building Recovery

Support méthodologique pour la réhabilitation des bâtiments

Computerisierte Vorgehensweise für die Sanierung von Altbauten

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SUMMARY
The increasing activities for the recovery of existing building patrimony have led to studies on the organization of activities with computerized tools. The research pursued two aims: a) the analytical identification of the various stages, operation duties and relevant operators involved in the restoration process; b) the implementation of the specific expert system. The main results have been: definition of an Intelligent Methodological Support System for Building Recovery, which controls/coordinates the interplay of single restoration stages by means of different tools and computerized or non-computerized methodologies, and the elaboration of a Building Computerized Card.

RÉSUMÉ
La généralisation des travaux de réhabilitation dans le domaine des bâtiments existants a entraîné des études approfondies, relatives à l'organisation des interventions à effectuer à l'aide de moyens informatiques appropriés. La recherche s'est développée en suivant deux objectifs: a) la détermination analytique des phases successives, des diverses modalités d'exécution et du personnel chargé des travaux de rénovation; b) la mise au point d'un système expert spécifique. Les résultats principaux sont traduits par la réalisation d'un prototype de ce système et par l'élaboration d'archives de données informatiques spécifiques au bâtiment.

ZUSAMMENFASSUNG
Die zahlreichen Sanierungsarbeiten des gesamten baulichen Erbes haben vertiefte Studien hinsichtlich Organisation der verschiedenen Eingriffe mit computerisierten Hilfsmitteln mit sich gebracht. Diesbezüglich hat sich die Forschung in zwei Richtungen entwickelt: a) die analytische Definition innerhalb des Sanierungsprozesses der aufeinanderfolgenden Phasen, der verschiedenen Ausführungsarten und der damit Beauftragten; b) die Entwicklung eines spezifischen Expertensystems. Als Hauptergebnisse gelten die Realisierung eines Prototyps dieses Systems und die Entwicklung eines computerisierten Datenarchives der einzelnen Gebäude, in dem man alle gespeicherten Informationen, Texte und Zeichnungen, aufrufen und z.B. für ein Wartungsprogramm oder einen Arbeitsauftrag zusammenstellen kann.

1. INTRODUCTION

The European Charter of the architectural patrimony, promulgated at the end of the european architectural patrimony congress, held in Amsterdam in 1975, and adopted by the committee of the European Council Ministers, states: "The European building/architectural patrimony is formed not only by the most prestigious monuments, but also by all the buildings which make up our cities and our traditional villages in their natural and constructed enviroment.... For quite some time, only the most important monuments have been preserved and restored, regardless of their context. They may, however, lose a great deal of their value if their context is altered. Moreover, groups of buildings, even without outstanding architectural features, may have enviromental qualities which contribute to give them a diversified and articulated artistic value. These groups of buildings must be preserved as such."
Such a principle is recalledby with the Italian law 457/1978 which specifies in the Fourth Title the General Rules for the rescue of the existing urbanistic and building patrimony; in the article 31 of this act, ordinary and exstraordinary maintenance, restoration and recovery, building and urbanistic restructuration fall within the interventions aimed to the building rescue. They are not simple interventions but specific processes characterized by specific, common aspects: the preexistence of the constructed object which must be investigated, measured, checked, i. e. known in-depth, before starting any building activities.
In the present paper, we do not address the specific terminology questions, rather we address the even more complex theoretical questions underlyng the rescue process. In particular, we have singled out and systematized the stages of the recovery process. The latter process was deemed methodologically more appropriate to exemplify a rescue activity which is supposed to be, on the basis of several statistical data, widespread represented across the entire nation.
The process of building recovery is made up by four main stages:
A- Pre-project stage: the building knowledge.
B- Planning stage: the project of interventions for building recovery.
C- Implementation stage: the interventions for building recovery.
D- Preservation stage.
The first stage encompasses the acquisition and synthesis of all the data relevant to the general identification of the building and to the identification of its degradation characteristics.These data will be used in the subsequent planning stage. The stage A is so important for the proper operation of the whole process (Restoration and Recovery) that has been acknowledged by the Italian Charter for Restoration, enclosed in recently approved building codes of historical cities, and also constitutes the main basis of the Territorial Informative System of the Enviromental and Architectural Property of the Central Institute for Catalog and Documentation for Cultural and Enviromental Patrimony. It can be easily seen that, for restoration and recovery, the knowledge stage entails absolutely new and specific characters and features as compared to those which inform the process of new constructions. In the latter case, it is necessary only to know both internal and external bonds, geotechnic and hydrogeological characteristics of the soil (soil conditions) and interactions with adhering buildings, if any.
The second stage constitutes the project of building recovery, i.e., the plan of those interventions deemed necessary for the preservation of the buiding or of some of its portions.
The third stage is made up by the actual activities of the construction site, carried out with particular methodologies and technologies which put into effect all the interventions planned in the second stage.
The fourth stage, which in theory lasts for ever, in other words until demolition, refers to the preservation of the building, i.e., constant control of the conservation state of the buiding or of some of its portions, ordinary and extraordinary maintenance.

2. THE SMIRNE SYSTEM

The methodological knowledge, the control and coordination of the four stages (delineated above), necessary to carry out the building rescue are the functions of the System for Intelligent Methodological Support of Building Rescue (the italian acronym, SMIRNE, will be used throughout). SMIRNE relies upon different tools and either computerized or non-computerized methodologies and is planned as the structure which unifies several rescue tools, which can really implement a support for many activities to be carried out. Some of these tools are knowledge based systems (KBS), others are simple programs.
The four main stages of recovery consist of several activities; each activity is performed by an agent, is supported by a tool, requires information and produces information, utilizes archives of knowledge.

The system's first task is, thus, to coordinate all the activities, assign them relevant agents and tools, connect activities and knowledge bases, control type and quality of the required and produced information.
Description of the four main stages of Recovery, of required and produced information, of supporting agents and tools, of background knowledge bases, constitutes a General Model of the SMIRNE System's domain (Fig. 1). For each stage, the system sets the relationships between knowledge bases of classes and knowledge bases of instances, which contain specific information about the given building and intervention patterns.
We talk about instance since the system sets relationships between a type of agent that can perform an activity and a particular agent that will perform it; between one type of required information and the specific information relative to a given building; between one type of recovery intervention and the particular intervention of a given building; between one type of technology required to carry out an intervention and the particular technology peculiar to a given building site, ecc.

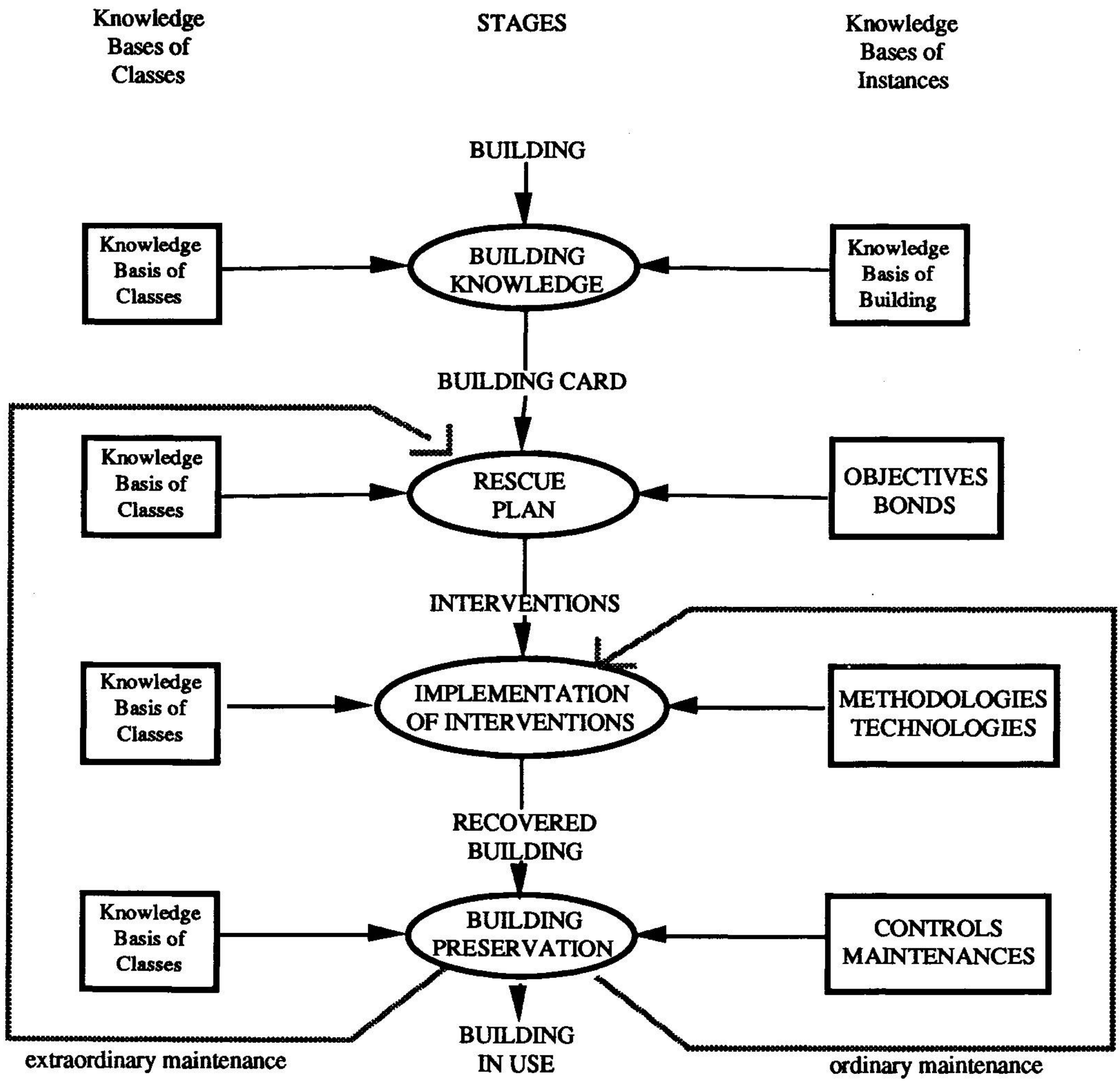

fig. 1 General Model of the SMIRNE System's domain: the model of recovery stages

In this model, each stage is related to a knowledge basis of classes; such knowledge bases contain description of the stage subdivided in activities and subactivities, of types of performing agents, of types of required tools, of types of information required and produced by these subactivities.
The knowledge bases are, thus, the main source of information for the fulfilment of the control tasks and coordination activities of the system.
Computerized tools supporting the activities of these stages are essentially traditional systems (CAD systems, data management systems, calculation programs) and intelligent sytems (knowledge based systems and more specific expert systems for diagnosis and planning).

2.1 The Model of the Building Knowledge Domain. Concepts and their relationships

The study carried out in this section of the project concerns the definition of the model of the building knowledge domain, i.e., concepts and their relationships.
The model of a generic information system is made up by some elements which can be led back to five typical concepts, and by the relationships among such concepts. The concepts are the following:
C1. Activity.
C2. Agent.
C3. Tool.
C4. Information (Data and/or Document).
C5. Archiv.
The concepts of Activity, Agent, Tool, Information, Archiv can be defined as "metaclasses", because they are generalizations of types of Activity, Agent, Tool, Information, Archiv which can be defined as "classes". The relationship between metaclasses and classes is an instance relationship, since one type of Activity, one type of Agent, one type of Tool, one type of Information, one type of Archiv, are instances of the concepts Activity, Agent, Tool, Information, Archiv (Table 1).
A peculiar Activity, a peculiar Agent, a peculiar Tool, a peculiar Information, a peculiar Archiv are, in turn, instances of classes or of types of Activities, Agents, Tools, Information, Archives.

METACLASS	CLASS	INSTANCE
Activity	Topographic finding	Topographic finding of the X building located in Y
Agent	Topographer	John Smith
Tool	Theodolite	Theodolite Zeiss T 500 model
Information Document	Cadastral Map	Cadastral Map of the X building located in Y
Datum	Topographic network point	P1(X1,Y1,Z1)

Table 1 Example of relationship involving metaclasses, classes and instances

A model which portraits a generic information system describing the five concepts (metaclasses) and their relationships can be thus, defined as Model of metaclasses; this model is a semantic network as far as the information structure is concerned (Fig. 2).

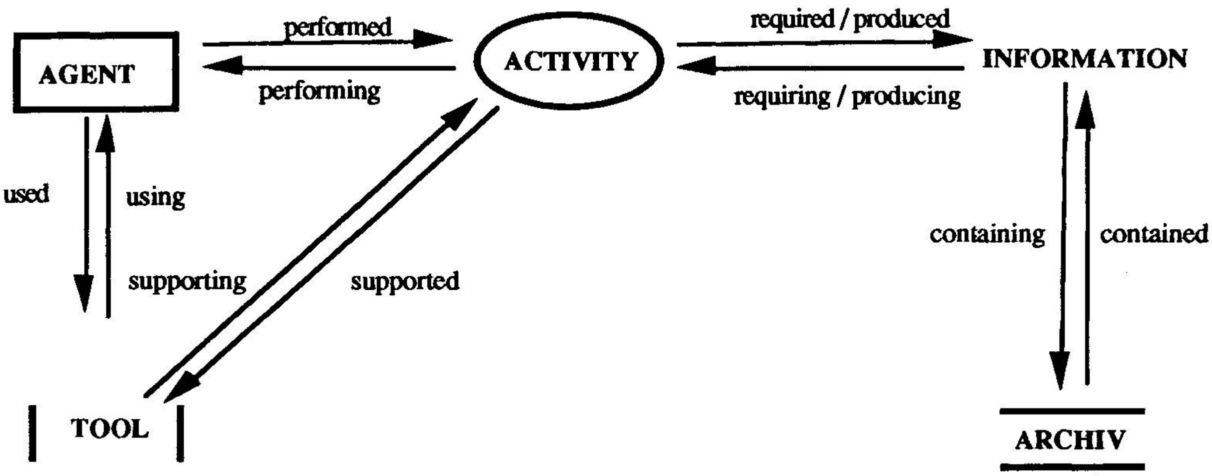

Fig. 2 Model of metaclasses as semantic network

The Activities are processes capable of accepting Data and/or Documents, manipulating them and otputting again Data or Documents.
The Agents have the task to carry out the Activities. In general, they can be people (e.g. the user, the planner, the historian, the physicist, etc.), programs (traditional programs, knowledge based system, expert systems, etc) or parts of the system.
The Tools support the Activities. They can be of various types, and can be classified as traditional tools and innovative tools, or as mechanic tools, electronic tools and computerized tools.
Document is any set of information which must be found or produced during the various Activities. Certificates, cartographies, regulations, to be found in agencies and libraries, as well as papers elaborated by the planner or by any other agent, fall within this concept.
Datum is any elementary information, generally rapresented by aggregates and classified as documents. For example, identification data of the building and of people who are legally bound to it, as well as evaluations made by the planner on the building preservation state, fall within this concept.
The Archiv is the original source (Documents and Data). For example, it can be a traditional archiv, (as municipal archiv, General Land Office archiv), or a data processing center, a library.

2.2 The stages of recovery process

A - The Building knowledge
The knowledge basis of classes is made up by description of the activities which concern the building knowledge and their relationships, and by description of the types of agents, tools, archives and information involved in this stage.
The knowledge basis of instances is made up by description of all the information on the particular building, by description of particular agents, tools, archives and information involved . The building knowledge is targeted to the compilation of the Building Computerized Card (Fig. 3).

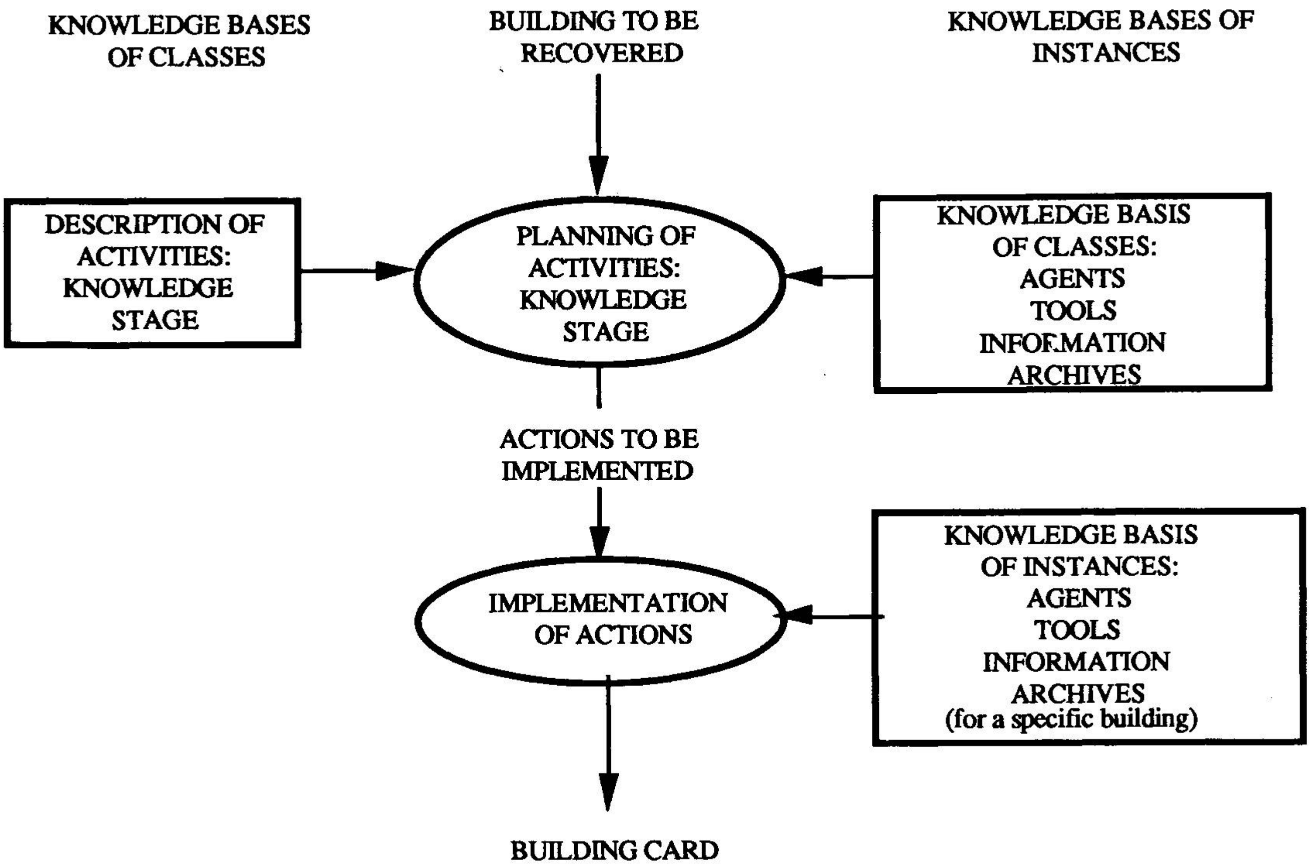

Fig. 3 The system model concerning the building knowledge stage

B - Planning of the recovery interventions
The knowledge basis of classes is made up by description of the activities which concern the planning of the recovery interventions and their relationships, and by description of the types of agents, tools, archives and information involved in this stage.
The knowledge basis of instances is essentially made up by description of recovery interventions and of internal and external bonds to the specific building. The planning of recovery interventions utilizes the Building Computerized Card, result of the previous stage and is targeted to the formulation of a list of recovery interventions.
C -Implementation of the recovery interventions.
The knowledge basis of classes is made up by description of the activities which concern the implementation of the recovery interventions and their relationships, and by description of the types of agents, tools, archives and information mainly involved in the accomplishment of the building site activities.
The knowledge basis of instances is thought to be made up by specific methodogies and technologies for the building site. The implementation of the interventions uses the description of interventions and is targeted to the production of the recovered building.
D - The building preservation
The knowledge basis of classes is made up by description of the activities which concern the building preservation and their relationships, and by description of the types of agents, tools, archives and information involved in this stage.
The knowledge basis of instances is basically made up by particular controls and maintenances which must be performed on the building during this stage.
In the case of ordinary maintenances, the system will resume the control at the stage of implementation of interventions.
In the case of extraordinary maintenances, the planning of the interventions should be probably reconsidered.

2.3 The system model concerning the building knowledge stage

Planning activities of the knowledge stage yields a description of the actions to be performed which represent activities to be developed (in sequential and/or parallel way) in order to yield the building card (Figs. 4, 5), the finding out the informations necessary to the activities, the supporting agents and tools required for the activities.

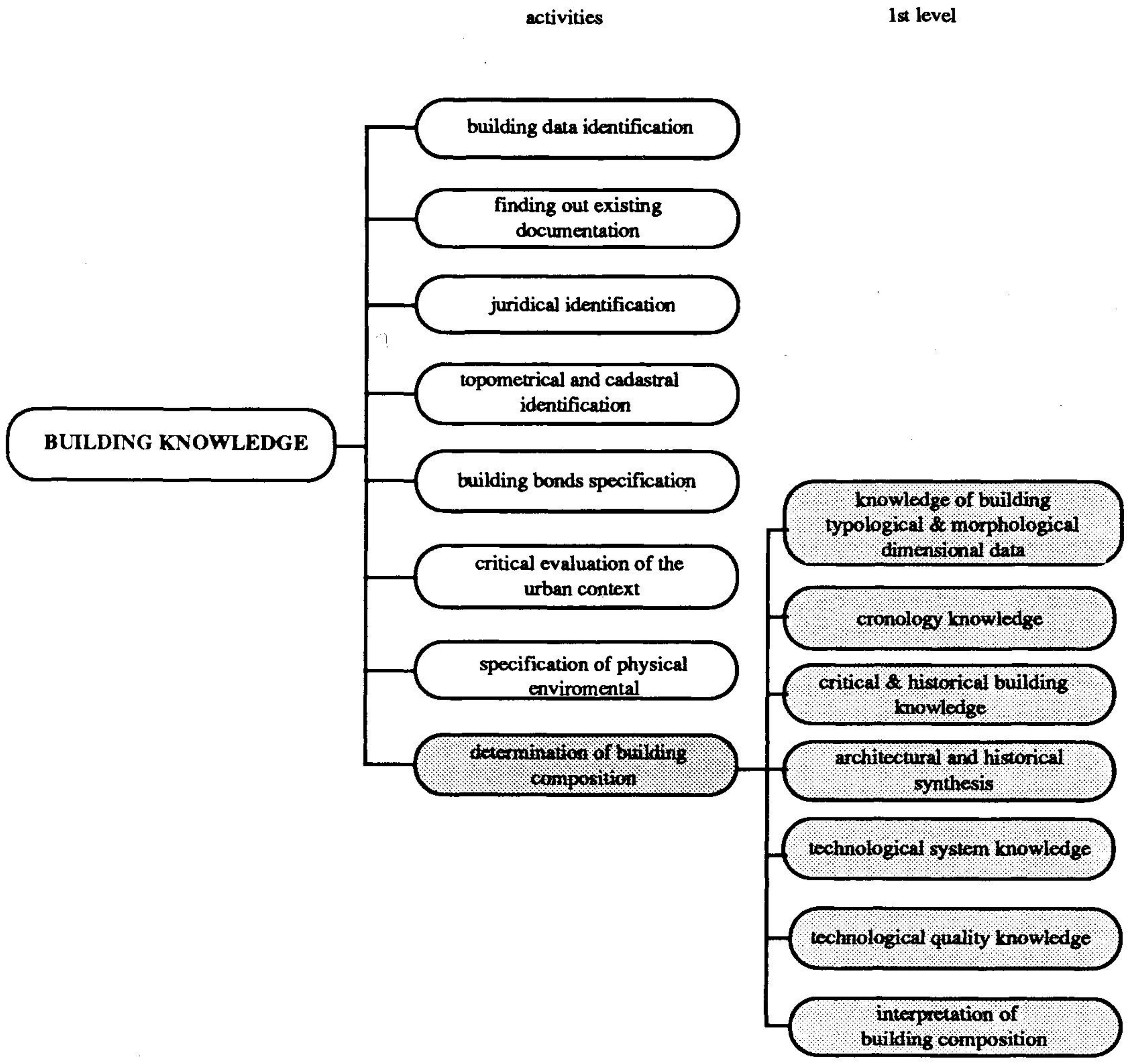

Fig. 4 Taxonomy of activities. Division in 1st level subactivities

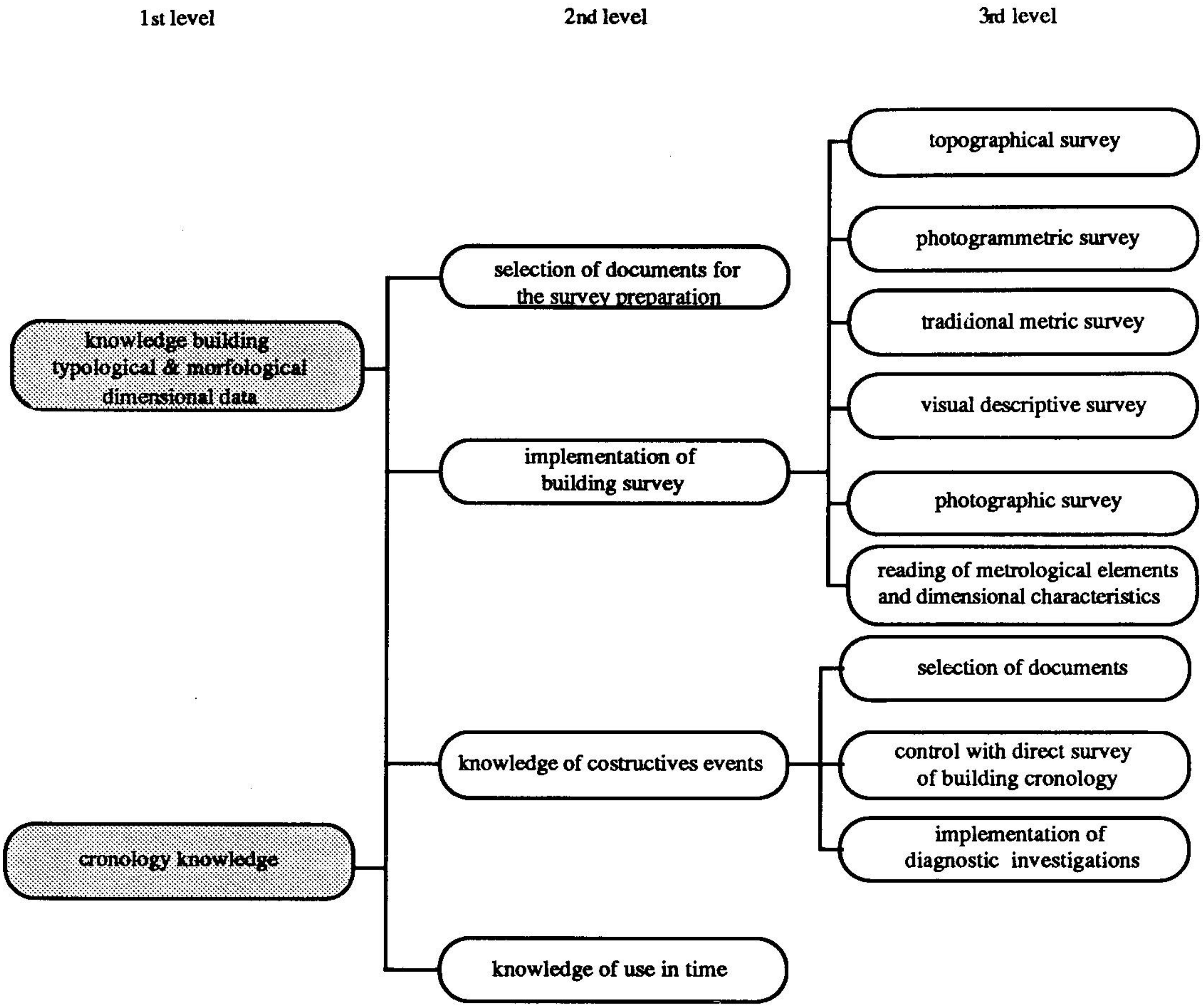

Fig. 5 Taxonomy of activities. Division in 3rd level subactivities

During the implementation of the action, a corrispondence between the knowledge base of the classes and the knowledge base of the instances is accomplished: types of information required by activities, types of agents, types of archives and types of supporting tools (knowledge basis of the classes) become information relative to the particular building and context, to specific agents, specific archives, and specific supporting tools (knowledge basis of the instances).

In particular, the system should fulfil, for a given activity, the following tasks among those concerning the building knowledge stage:

- Identification of the type of agent(s) which can perform the activity.
- Identification of the type of tool(s) supporting this activity.
- Identification of the type of information requested and yielded by the activity
- Identification of the container of the requestested information (usually a type of archiv).

Based on the particular building under consideration and on the particular context where it is placed, the system should provide:

- Identification of the particular agent(s), belonging to a given type, which will perform the activity.
- Identification of the particular tool(s), belonging to a given type, which will support the activity.
- Identification of the specific requested information, belonging to a given type and of the specific container (e.g,. a particular archiv), where it is placed.

Once accomplished such operations, the system will control the proper development of the activities.

2.4 Conditions for computerized filing of knowledge

It is necessary to lay out the computerized procedures for filing and for subsequent finding out graphical, pictorial and textual information relevant to a given buiding, in order to create a Building Computerized Card. The Card will help to transform fragmentary knowledge in systematized and aggregated knowledge, targeted to the use of the information for the planning stage, for the management of the building patrimony, for historical or typological studies.The computerized archiv should perform as vital archiv, i.e., in continuous growth and modifiable in time. In particular, the archiv must function as support to stages subsequent to that of knowledge, in the context of the recovery process (Tables 2, 3).

ACTIVITIES	DATA and/or DOCUMENTS	ARCHIVES FORMAT
topographic finding	topographic survey	Vectorial Drawings
photogrammetric finding	photogrammetric survey	Vectorial Drawings
traditional metric finding	table of traditional metric survey	Vectorial Drawings Alphanumerical Data
visual descriptive finding	descriptive report	Alphanumerical Data Raster Pictures
photografic finding	inventory of photografic cards of actual conditions	Raster Pictures Alphanumerical Data
reading of metrological and dimensional characteristic	synthesis report of dimensional characteristic	Alphanumerical Data Raster Pictures

Table 2 Correspondence among 3rd level subactivities, yielded data and documents, and their format filing: implementation of building survey

ACTIVITIES	DATA and/or DOCUMENTS	ARCHIVES FORMAT
selection of documents	pre-existing building list historical regest historical constructive tables tables of restorations tables for use in time tables of actual use	Alphanumerical Data Raster Pictures Vectorial Drawings
control with direct survey of building chronology	chronology survey	Alphanumerical Data Raster Pictures Vectorial Drawings
implementation of diagnostic investigations	certificates of diagnostic investigations	Alphanumerical Data Raster Pictures
knowledge of use in time	regests of tables with use in time	Alphanumerical Data Raster Pictures Vectorial Drawings

Table 3 Correspondence among 3rd level subactivities, yielded data and documents, and their format filing: knowledge of constructive events

There is not a single data base, rather there are several and smaller data bases closely related to each other, so that they can be more easily modified or integrated, should new requirements occur; they are easily managed by a medium-power graphic station because the whole system is lighter and allows shorter response times; finally, they make up an easily repeteable structure.
In the specific case, however, the division takes place in the following data bases, according to this distinction:
1 - alphanumerical data
2 - vectorial drawings
3 - raster images of: maps, historical drawings, old regests, historical and contemporary pictures.
The major advantage of the data base is to establish relationships between bodies of information also coming from different archives and, as in this case, to emphasize possible interactions among structural, historical and technological data, in a more immediate fashion than usual paper sources. The program however, with respect to its external interface, attempts to keep an approach comparable to that of normal paper information, by leading the hypothetical user to the various possibilities presented by the data base with the simplest menus and with an always available help function.

3. CONCLUSIONS

We chose the buildings of the Botanical Garden (built in 1545), destined to become headquarters of the University of Padua Scientific Museums, in order to test the prototype of the computerized archiv.
A preliminary evaluation of consulted documents has made possible to recognize the condition/format of filing and to test a preliminary draft of computerized archiv.
In the archiv, all available data are arranged in a structure compatible not only for filing but also for the systematic and comparative research of data, targeted ether to the understanding of historical and architectonic features of the building or to provide cognitive support for a possible intervention of recovery of maintenance.

4. NOTES

Throughout the text we made use of several words whose meaning is detailed as follows:
Rescue refers to the global process, whereas restoration, recovery, preservation and restructuration refer to individual steps of the rescue.

5. ACKNOWLEDGEMENTS

Work supported by funds from the National Research Council (CNR) "Target Project for Building" (contract no. 89.00270.64).
Thanks are due to E. Rinaldi for the implementation of the first prototype of the SMIRNE System, and to P. Volpe and M. Fasciano for critical readings of the manuscript.

Durability Evaluation System of Aged Water Supply Pipes

Système d'évaluation de la durabilité d'anciennes conduites d'eau

Ermittlung der Dauerhaftigkeit gealterter Wasserversorgungsleitungen

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SUMMARY

The durability of cast iron water supply pipes is affected not only by service duration, but also by corrosion environment, wheel loads due to traffics, etc. This paper proposes a two-step procedure to evaluate the durability of small diameter cast iron pipes for establishing reasonable replacement criterion. The first step uses fuzzy sets theory to combine expert knowledge with a statistical model. It can be used for the first screening of less durable pipe links. The second step is based on a series of investigation, analysis and experiment and can be used for detailed evaluation.

RÉSUMÉ

La durabilité des canalisations en fonte pour l'approvisionnement en eau est influencée non seulement par la durée d'utilisation, mais encore par l'atmosphère corrosive, les charges mobiles de véhicules du trafic routier, etc. Afin d'apprécier la durabilité des tubes de petit diamètre d'une conduite d'approvisionnement en eau, cet article propose un procédé en deux phases afin de fournir un critère raisonnable de remplacement. Dans la première phase, la connaissance d'experts est combinée à un modèle statique, à partir de la théorie des ensembles flous; ceci permet de découvrir les raccords de tubes laissant le plus à désirer. Pour une appréciation plus approfondie, la seconde phase se base sur des investigations en série, avec calculs et essais à l'appui.

ZUSAMMENFASSUNG

Die Dauerhaftigkeit gusseiserner Wasserversorgungsrohre ist nicht nur durch die Nutzungsdauer, sondern auch durch korrosive Atmosphäre, Verkehrsradlasten usw. beeinflusst. Der Beitrag schlägt zur Beurteilung der Dauerhaftigkeit von Rohren kleinen Durchmessers ein zweistufiges Vorgehen vor, mit dem sich ein vernünftiges Kriterium für den Auswechselbedarf aufstellen lässt. Im ersten Schritt wird mittels Fuzzy-Set-Theorie Expertenwissen mit einem statischen Modell verknüpft, um in einem ersten Durchgang die anfälligeren Rohverbindungen zu sichten. Für die genauereAuswertung werden in einem zweiten Schritt Reihenuntersuchungen mit Berechnungen und Experimenten vorgenommen.

1. INTRODUCTION

Water supply pipes (WSP) were first installed in Japan about a century ago and have extended about 8000 km even in Nagoya City, a major city with 2 million inhabitants. Especially in 1950s and 1960s large amounts of cast iron pipes were installed. The design life of these pipes was 38 years and quite a few breaks occurred in them recently. In order to ensure better serviceability it becomes urgent nowadays to replace them year by year based on their durability.

The durability of cast iron WSP is affected not only by service duration, but also by corrosion environment, wheel loads due to traffics etc., as shown in Fig.1. Unlike such structures as bridges, visual inspection is impossible when their durability is evaluated. In the past, mainly three approaches have been adopted in the evaluation, i.e. descriptive analysis, predictive analysis and physical analysis [1]. The descriptive analysis is to analyze the frequency and pattern of pipe breaks and it can hardly consider several influential factors simultaneously. The predictive analysis uses statistical method to build evaluation model, but it is not easy to determine the contributing factors and to obtain the corresponding data. The physical analysis employs engineering-based algorithm and it gives more reliable measure, provided that the failure mechanism is clearly understood and the related factors are easily evaluated.

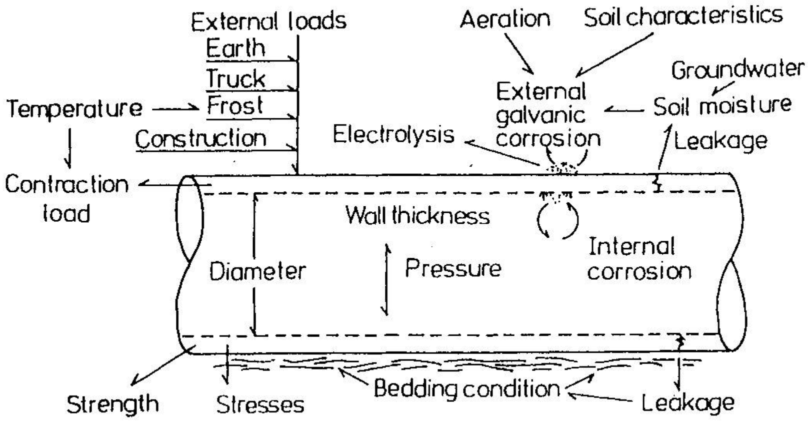

Fig.1 Conceptual model of structural condition of cast iron WSP [1]

This paper proposes a two-step procedure to evaluate the durability of small diameter (less than 400 mm) cast iron WSP. In the first step, fuzzy sets theory is applied to combine the experts' knowledge on corrosion environment factors with a statistical evaluation model. This step requires only qualitative information and can be used for the first screening of less durable pipe links. The second step uses the approach of physical analyses and is based on a series of sampling investigation, stress analysis and experiment. It can be used for detailed evaluation.

2. THE FIRST STEP - A PREDICTIVE MODEL USING FUZZY SETS THEORY

2.1 General

In 1984, the Japanese Ministry of Health and Welfare organized a nationwide sampling survey on aged WSP. An evaluation model called Model 4-7 was built from the data on 912 pipe links, half of which had not experienced breaking and the other half broke seemingly due to non-corrosion reasons [3]. The quantification theory was used to build the model and the objective was selected as whether a break has occurred in the pipe link. The factors included in the model are type of material and joint, diameter, depth of earth covering, traffic of large vehicles, maximum hydraulic pressure and service duration, and corrosion environment factors were excluded. The model showed a correct evaluation rate of 72.1 percent on the 912 sample pipe links.

In this step, first we assume that the influence of those factors can be evaluated by the Model 4-7, then we try to combine the influence of corrosion environment with it in order to obtain a general model. This approach is justified because we can avoid the expensive and difficult process to consider corrosion environment factors in a statistical model [3].

Through an extensive literature survey, we distinguished the environmental factors that influence the corrosion of small diameter cast iron WSP as shown in Fig.2 [4]. It is difficult to evaluate these factors quantitatively, but it seems possible for a site technician to evaluate them qualitatively by using specified vocabularies according to a guideline. Besides, the weight of 6 parallel factors (i.e. aeration difference along the pipe link, nonhomogeneity of backfill, stray current, bi-metallic corrosivity, concrete/soil corrosivity, corrosivity of water) may be evaluated by experts. In order to take advantage of this, we decided to use fuzzy sets theory.

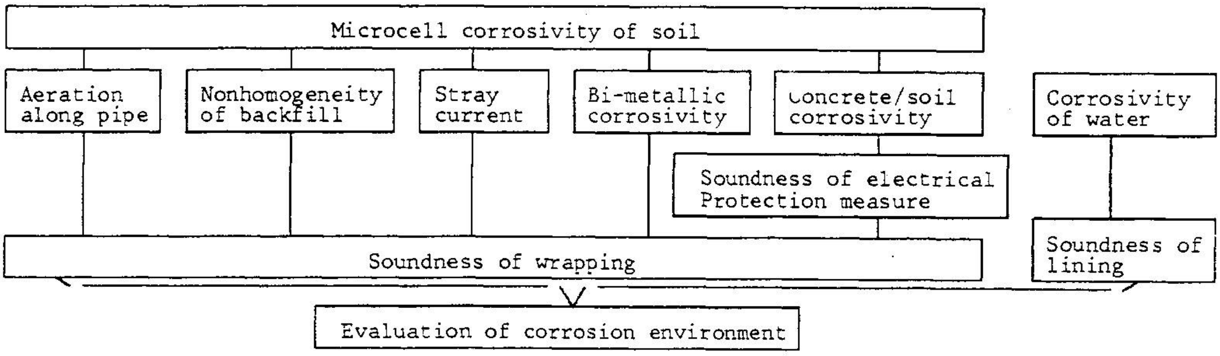

Fig.2 The conceptual structure of corrosion environment factors

In the study, engineers in Nagoya City Waterworks Bureau who had worked for 10 to 32 years with field work experience ranging from 2 to 24 years served as experts. The vocabularies used for evaluation were selected and their membership functions were evaluated as shown in Fig.3. Then the experts used

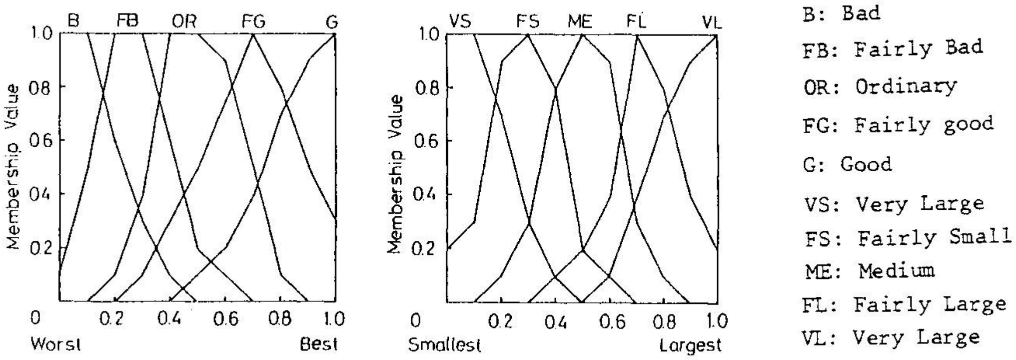

Fig.3 Membership functions of evaluation vacabularies

them to evaluate the weight of the six parallel factors. The results are shown in Fig.4.

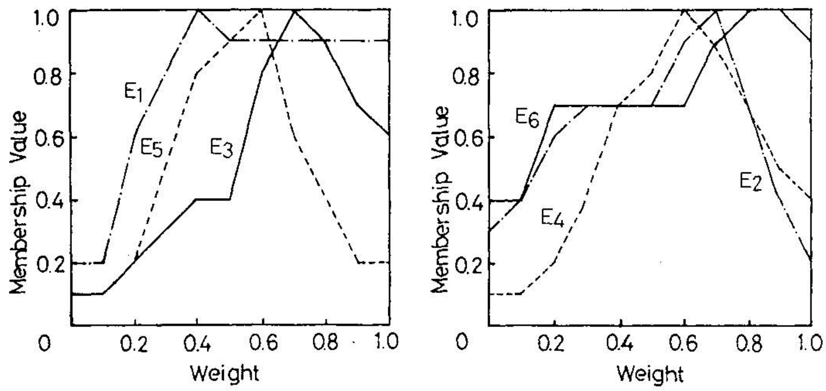

Fig.4 Weight of corrosion environment factors

2.2 The predictive model

In order to evaluate the severeness of corrosion environment of pipes based on Fig.2, the following equation is used.

$$P=P_a \oplus P_b \tag{1}$$

where

$$P_a=(\neg T_2)\cap\{[\bigcup_{i=1}^{4}(S_i\cap E_i)]\cup[S_5\cap E_5\cap(\neg T_1)]\}\cap S_0$$

$$P_b=E_6\cap S_6\cap(\neg T_3)$$

The sizes S_0 to S_6, T_1 to T_3 and the weights E_1 to E_6 are explained in Table 1 and they are all fuzzy sets. The symbols $\neg$, $\cap$ and $\cup$ indicate supplement, interaction and union, respectively. The symbol $\oplus$ is the algebraic sum. The support of the fuzzy sets takes values of 0, 0.1, 0.2, to 1.

Table 1 Corrosion environment factors

No.	Factors	Weight	Size
1	Aeration difference along pipe link	E_1	S_1
2	Nonhomogeneity of backfill	E_2	S_2
3	Stray current	E_3	S_3
4	Bi-metallic corrosivity	E_4	S_4
5	Concrete/soil corrosivity	E_5	S_5
6	Corrosivity of water	E_6	S_6
7	Microcell Corrosivity of soil	-	S_0
8	Soundness of electrical corrosion protection measure	-	T_1
9	Soundness of wrapping	-	T_2
10	Soundness of lining	-	T_3

The result of durability evaluation Q that includes the influence of corrosion environment is computed by using fuzzy composition as follows.

$$Q = P \circ R \tag{2}$$

where R is the fuzzy relation obtained by trial-and-error method based on the result of a field survey that the experts took part in. In the field survey, 14 pipe links in various corrosion environment were selected, and the experts evaluated the corrosion environment factors and the durability rank of each pipe link. In the present model, R is adopted as shown in Table 2 and corresponds to the following meaning.

If P is very small, then Q is small;
If P is ordinary, then Q is medium;

If P is fairly large, then Q is large.
Q has the following form, and the values of Q as "small", "medium" and "large" were defined after Brown [5].

$$Q = a_1/L_o + a_2/(L_o-1) + a_3/(L_o-2) + a_4/(L_o-3) \quad (3)$$

where L_o is the rank obtained by using the Model 4-7.

Table 2 Fuzzy relation for cast iron WSP

	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Lo	1	1	0.7	0.3	0.5	0.5	0.5	0.3	0.2	0.2	0.2
Lo-1	0.5	0.5	0.5	0.3	0.5	0.5	0.6	0.6	0.6	0.4	0.2
Lo-2	0.2	0.2	0.2	0.3	0.5	0.5	0.7	0.8	0.8	0.4	0.2
Lo-3	0	0	0.1	0.3	0.5	0.5	0.7	1	0.8	0.4	0.2

The durability rank is obtained by deffuzzifying Q using the gravity center method.

$$L = \left[\sum_{i=1}^{m} (L_o-i+1) \cdot \mu_Q(L_o-i+1)\right] \Big/ \left[\sum_{i=1}^{m} \mu_Q(L_o-i+1)\right] \quad (4)$$

where m equals to L_o if $L_o \le 4$, 4 otherwise.

The results of evaluation on the 14 pipe links by the Model 4-7 and the present model are shown in Table 3. The present model showed a different rank with the Model 4-7 and is closer to the average durability rank evaluated by the experts. Moreover, prediction by using each expert's evaluation on the corrosion environment factors varies within one rank.

Table 3 Durability rank of 14 pipe links

Item \ Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Average evaluation by experts	4	3	3	3	2	2	3	3	4	4	3	3	3	3
Prediction by the Model 4-7	5	5	5	5	5	5	5	5	5	4	5	5	2	4
Prediction by average expert	3	4	3	3	3	3	4	3	4	3	3	3	2	2
Prediction by expert A	-	4	3	3	3	3	3	3	3	2	4	4	1	2
B	3	4	4	4	3	4	4	4	4	3	4	4	1	2
C	3	3	3	-	-	-	-	3	4	3	3	3	1	2
D	3	4	3	3	3	4	4	3	3	3	3	3	2	2
E	-	3	3	-	-	-	-	-	-	-	-	-	-	-

3. THE SECOND STEP - A PHYSICAL MODEL BASED ON FAILURE MECHANISM

3.1 The failure mechanism of small diameter cast iron WSP [6]

According to the break records in Nagoya City, about 91 percent of the breaks in small diameter cast iron WSP were due to circumferential cracks. In order to clarify the failure mechanism, we carried out a series of investigation, analysis and experiment as stated below.

(1) Sample investigation
Eighty nine pipe links in Nagoya City were randomly selected for detailed investigation. For each pipe link, a 1 m long sample pipe was excavated and a 15 cm long part of it was sand-blasted for the measurement of corrosion pits. The statistical theory of extreme values was used to compute the pipe length of having a through-wall pit [7].

(2) Stress analysis considering local soft and hard foundation
According to Takagi et al., the static strain in the axial direction of pipes

under wheel loads, which contributes to the circumferential crack, may be obtained by considering the pipe link as a beam on elastic foundation [8]. Using the method, we carried out a parametric analysis on a pipe link of 100 mm diameter to examine the static strains under various influential factors. In the analysis, local hard and soft foundation were considered; the former simulates a rock, concrete block or other cross pipes in the bedding, and the latter considers local washing caused by water leakage.

(3) Test of installed small diameter pipes under dynamic loading
The dynamic effect of wheel loading depends on many factors and it is very difficult to be evaluated analytically. In the study, we installed 100 mm diameter ductile iron pipes in a depth of 0.8 m and measured the strains under three modes of dynamic loading (normal rolling, braking and bumping), as well as under static loading of a dump truck. The dynamic effect on the strain of pipes were evaluated by the impact factor β defined as follows.

$$\beta = \varepsilon / \varepsilon_{st} \tag{5}$$

where ε_{st} is the strain under static loading and ε is the corresponding strain under dynamic loading. Both are the axial strain of pipes.

(4) Bending fatigue test of aged cast iron pipes
It was known from the above that the strain comparable to the ultimate strain of pipe material may occur only under the combination of extremely severe conditions for each influential factor. However, pipes that do not have such combination actually broke occasionally. So we suspect that fatigue is the cause of such failure. Thus we carried out bending fatigue tests on 13 aged pipes of 100 mm diameter, which were in service for 19 to 40 years. The test results were compared with the previous ones on the new material of pipes by Kusafuka et al. [9].

3.2 The physical model

Corresponding to the static failure and fatigue failure of small diameter cast iron WSP, two limit states may be defined, i.e. static limit state and fatigue limit state.

For the static limit state, we define a ratio D_1 as shown below.

$$D_1 = \varepsilon_{cs} / \varepsilon_s \tag{6}$$

where ε_{cs} is the static strength of cast iron WSP and ε_s the possible maximum strain in the pipe link. In this study, we use ε_{cs} as 1730 μ which is obtained by dividing the strength by the elastic modulus of cast iron.

For the fatigue limit state, we define a ratio D_2 as follows.

$$D_2 = \Delta\sigma_{cf} / (E \cdot \Delta\varepsilon_f) \tag{7}$$

where $\Delta\sigma_{cf}$ is the fatigue strength of cast iron WSP and $\Delta\varepsilon_f$ the possible maximum nominal strain range in the pipe link. In the above-mentioned experiment, we obtained the S-N diagram as shown in Fig.5. The fatigue strength corresponding to 2 million cycles is about 30 MPa with the average survice duration of 33 years. It is obvious that the slope of the S-N diagram is very small compared to that of structural steel. This phenomenon is also observed in the previous experiment on new pipe material. Based on these results, we adopt $\Delta\sigma_{cf}$ as the fatigue strength corresponding to 2 million cycles and assume that it varies with the service duration as shown in Fig.6, in which the influence of the stress concentration due to corrosion pits is included.

Although 2 million cycles are assumed, the pipes may fail after a much smaller number of cycles because of the small slope of S-N diagram and the scatter in fatigue strength.

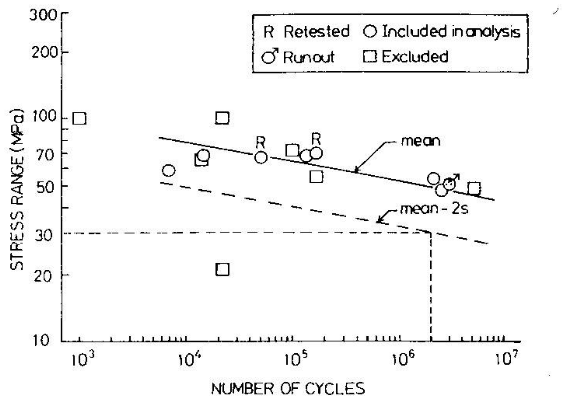

Fig.5 S-N diagram of 13 aged cast iron WSP

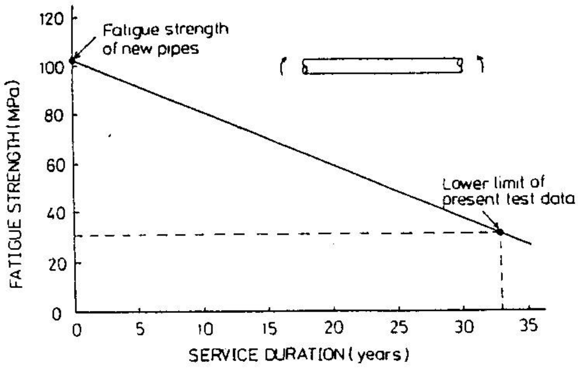

Fig.6 Assumed fatigue strength reduction of cast iron WSP with service duration

Here, ε_s and $\Delta\varepsilon_f$ can be computed as follows.

$$\varepsilon_s = \alpha(\beta \cdot \varepsilon_0 + \varepsilon_i) \tag{8}$$

$$\Delta\varepsilon_f = \beta \cdot \varepsilon_0 \tag{9}$$

where ε_i is the initial strain in the pipes due to installation and temperature change, ε_0 is the possible maximum static strain caused by wheel load, β is the impact factor, and α is the stress concentration factor caused by internal corrosion pits. By assuming that the internal corrosion pits have the shape of half sphere, which is conservative for most of the corrosion pits, α may be obtained [10].

The durability ratio D of the pipe link is assumed to be the smaller value between D_1 and D_2, i.e.

$$D = \min(D_1, D_2) \tag{10}$$

It is noted that the larger is D, the more durable is the pipe link, and that the pipe link is susceptible to failure when its D is smaller than 1.

The flow chart for using the physical model is shown in Fig.7. The major factors are evaluated by using the knowledge we obtained in the study.

4. EXAMPLES

4.1 Example of using the predictive model

A pipe link is in the condition as shown in Table 4. Its durability is evaluated by using the predictive model.

(1) Prediction by using the Model 4-7
The detail is described elsewhere [2]. We obtain L_0 = 5.

(2) Computation of P
The severeness of corrosion environment P is computed by using Eq.1, as shown in Table 5.

(3) Computation of the durability rank

By using Eq.2, we obtain the result of durability evaluation Q as a fuzzy set.

$$Q = 0.7/5 + 0.5/4 + 0.5/3 + 0.5/2$$

Then by using Eq.4, we get the durability rank L.

$$L = (5X0.7 + 4X0.5 + 3X0.5 + 2X0.5)/(0.7 + 0.5 + 0.5 + 0.5) = 4$$

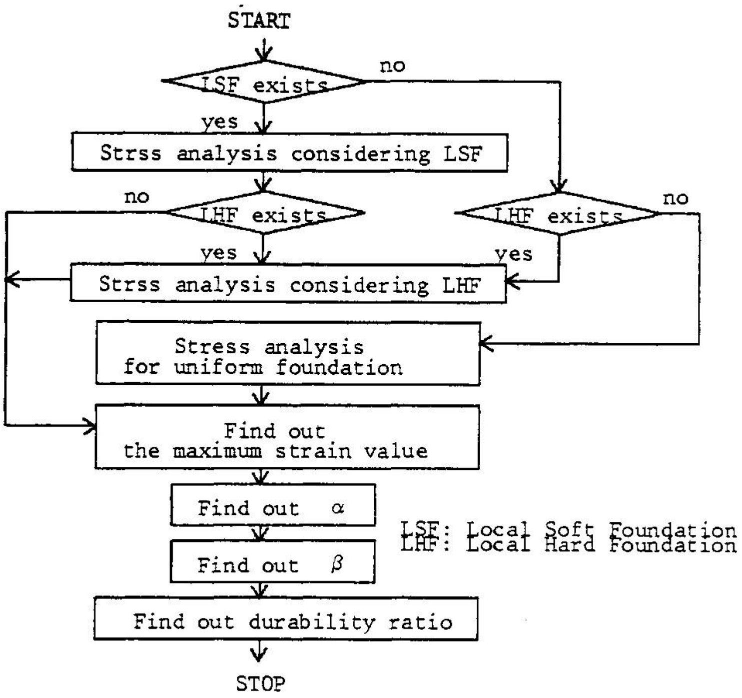

Fig.7 Flow chart for evaluating the durability of a pipe link using the physical model

Table 4 Condition of a pipe link

Item	Value	Item	Value	Item	Value
Type of material and joint	CIP-M*	S_0	Medium	S_6	Fairly Small
Diameter (mm)	75	S_1	Fairly Small	T_1	Trivial
Depth of earth covering (m)	1.2	S_2	"	T_2	Bad
Traffic of large vehicles	None	S_3	Trivial	T_3	Ordinary
Maximum hydraulic pressure (N/cm^2)	34.3	S_4	Very Small		
Service duration (years)	19	S_5	Very Small		

* CIP-M indicates cast iron pipes with mechnical joints

4.2 Examples of using the physical model

Seven pipe links in Nagoya City are evaluated by using the physical model. The conditions for evaluation and the evaluation process are shown in Table 6. The resulted durability ratio is between 0.55 and 1.81 depending on the severeness of static and fatigue loading condition, and the combination of various factors jointly affected the durability.

This model should be further verified by comparing the evaluation results with the reality. However, the influential factors considered here seems to be plausible in the detailed evaluation on the durability of small diameter cast iron WSP.

Table 5 Computation of P

Item \ SM*	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	Note
S_1	0.2	0.3	0.9	1	0.8	0.2	0.1	0	0	0	0	FS
E_1	0.2	0.2	0.6	0.8	1	0.9	0.9	0.9	0.9	0.9	0.9	
$P_1=S_1 \cap E_1$	0.2	0.2	0.6	0.8	0.8	0.2	0.1	0	0	0	0	
S_2	0.2	0.3	0.9	1	0.8	0.2	0.1	0	0	0	0	FS
E_2	0.3	0.4	0.6	0.7	0.7	0.7	0.9	1	0.7	0.4	0.2	
$P_2=S_2 \cap E_2$	0.2	0.3	0.6	0.7	0.7	0.2	0.1	0	0	0	0	
S_3	0	0	0	0	0	0	0	0	0	0	0	TR
E_3	0.1	0.1	0.2	0.3	0.4	0.4	0.8	1	0.9	0.7	0.6	
$P_3=S_3 \cap E_3$	0	0	0	0	0	0	0	0	0	0	0	
S_4	1	1	0.7	0.3	0.1	0	0	0	0	0	0	VS
E_4	0.1	0.1	0.2	0.3	0.4	0.4	0.8	1	0.9	0.7	0.6	
$P_4=S_4 \cap E_4$	0.1	0.1	0.2	0.3	0.1	0	0	0	0	0	0	
S_5	1	1	0.7	0.3	0.1	0	0	0	0	0	0	VS
E_5	0.1	0.1	0.2	0.5	0.8	0.9	1	0.6	0.4	0.2	0.2	
$\neg T_1$	1	1	1	1	1	1	1	1	1	1	1	$\neg$TR
$P_5=S_5 \cap E_5 \cap (\neg T_1)$	0.1	0.1	0.2	0.3	0.1	0	0	0	0	0	0	
S_0	0	0	0.1	0.3	0.8	1	0.9	0.3	0.1	0	0	M
$P_0=S_0 \cap (\cup P_i)$	0	0	0.1	0.3	0.8	0.2	0.1	0	0	0	0	
$\neg T_2$	0	0	0.4	0.7	0.9	1	1	1	1	1	1	$\neg$B
$P_a=P_0 \cap (\neg T_2)$	0	0	0.1	0.3	0.8	0.2	0.1	0	0	0	0	
S_6	0.2	0.3	0.9	1	0.8	0.2	0.1	0	0	0	0	FS
E_6	0.4	0.4	0.7	0.7	0.7	0.7	0.7	0.9	1	1	0.9	
$\neg T_3$	1	1	0.9	0.6	0	0	0.1	0.7	0.9	1	1	$\neg$OR
$P_b=S_6 \cap E_6 \cap (\neg T_3)$	0.2	0.3	0.7	0.7	0.2	0	0.1	0	0	0	0	
$P=P_a \oplus P_b$	0.2	0.3	0.7	0.8	0.8	0.2	0.2	0	0	0	0	

* SM indicates support of membership function.

Table 6 Examples of using the physical model

Item \ Sample No.	1	2	3	4	5	6	7
· Diameter (mm)	100	100	100	100	100	100	100
· Joint type	S	S	S	S	S	S	S
· Depth (m)	0.7	0.9	1.3	0.7	0.8	0.7	0.9
· Service duration (years)	36	29	28	30	28	30	32
· t_e (years)	36	12	20	18	19	21	27
1) t (mm)	7.5	9.0	9.0	7.5	7.5	7.5	7.5
Pipe length (m)	4.0	4.0	4.0	4.0	4.0	4.0	4.0
2) Soil type	sand	sand	sand	sand	silt	silt	silt
N value	28	1	4	15	4	3	2
Reaction coefficient (N/cm^3)	186.2	9.8	33.3	105.8	33.3	25.5	17.7
3) Length of LSF (m)	0	0	0	0	0	3.0	0
4) Length of LHF (m)	0.2	0.2	0.2	0.2	0.2	0.2	0.2
5) Road condition	VN	P	VR	P	VN	VN	VR
6) Maximum weight of trucks (kN)	196	196	196	196	196	196	196
· ε_i (μ)	400	400	400	400	400	400	400
· ε_0 (μ)	83	114	56	83	103	305	116
· $b/t = 0.83 \cdot t_e^{0.56}$	0.83	0.37	0.49	0.56	0.57	0.61	0.71
· α	3.0	2.1	2.1	2.2	2.2	2.3	2.4
· β	2.0	2.0	1.0	3.0	1.0	2.0	3.0
· $\varepsilon_s = \alpha(\beta \cdot \varepsilon_0 + \varepsilon_i)$ (μ)	1689	1318	957	1427	1106	2323	1795
· $\Delta\varepsilon_f = \beta \cdot \varepsilon_0$ (μ)	166	228	56	249	103	610	348
· $\Delta\sigma_{cf}$ (MPa)	29.4	35.8	37.2	36.3	37.2	36.3	33.3
$D_1 = \varepsilon_{cs}/\varepsilon_s$	1.02	1.31	1.81	1.21	1.56	0.75	0.96
$D_2 = \Delta\sigma_{cf}/(E \cdot \Delta\varepsilon_f)$	1.64	1.46	6.17	1.35	3.35	0.55	0.89
D (Durability ratio)	1.02	1.31	1.81	1.21	1.56	0.55	0.89

Note. S: socket joint VN: no repair of pavement VR: repaired pavement P: pedestrian t_e: duration before lining t: nominal wall thickness $E = 10.8\ N/cm^2$

5. SUMMARY

In the study, the authors proposed a two-step procedure for evaluating the durability of small diameter cast iron WSP based on a series of investigation, analysis and experiment. The following summarizes the main findings.

1) As the first step, a predictive model that combines a statistical evaluation model and experts' knowledge was proposed. This model makes it easy to include the corrosion environment factors and can be used for the first screening of the pipe links that are less durable.

2) Small diameter cast iron WSP break mainly as a result of static failure or fatigue failure. The major influential factors are service duration, bedding condition, surface condition of road, wheel loads, stress concentration caused by internal corrosion pit, reduction in fatigue strength, etc.

3) As the second step, a physical model based on static limit state and the fatigue limit state was proposed. This model includes the knowledge that we obtained from a series of investigation, analysis and experiment, and can be used for detailed evaluation on the durability of small diameter cast iron WSP.

ACKNOWLEDGMENT

This study was supported by Nagoya City Waterworks Bureau. The cooperation from the staffs who took part in the field survey, organized the investigation or helped the loading test is highly appreciated.

REFERENCES

1. AWWA RESEARCH INSTITUTE FOUNDATION, Water Main Evaluation for Rehabilitation/Replacement, pp.55-85, 41-44, 1986.
2. DEPARTMENT OF WATERWORKS AND ENVIRONMENT, JAPANESE MINISTRY OF HEALTH AND WELFARE, Report on the Development of Renewal System for Water Supply Pipes, 1987 (In Japanese).
3. YAMADA K. and MA ZHILIANG et al., A Comprehensive Approach to Evaluating the Durability of Water Supply Pipes, Journal of JSCE, Vol.416, pp.375-384, 1991 (In Japanese).
4. ASAKURA S. et al., Mechanism and Conuntermeasures of Corrosion (No.2-4), Pipeline Information, No.4, pp.22-27, No.5, pp.34-40, 1985; No.6, pp.35-40, 1986 (In Japanese).
5. BROWN C.B., A Fuzzy Safety Measure, Journal of the Engineering Mechanics, ASCE, Vol.105, No.EM5, pp.85-872, Oct.1979.
6. MA ZHILIANG, Durability Evaluation of Water Supply Pipes for Establishing the Replacement Criterion, Doctoral Dissertation of Nagoya University, Mar. 1992 (In Japanese).
7. AZIZ P.M., Application of the Statistical Theory of Extreme Values to the Analysis of Maximum Pit Depth Data of Aluminum, Corrosion, Vol.12, pp.495-506, 1956.
8. TAKAGI S., Analysis of the Axial Strain in the Pipe Links under Wheel Load, Journal of JSCE, No.403, pp.29-38, 1991 (In Japanese).
9. KUSAFUKA S., Fatigue Properties of Ductile Cast Iron Pipe Material, Material for No.63 Symposium on Ductile Cast Iron, 1980 (In Japanese).
10. NISHIDA M., Stress Concentration, Morishita Publishing Inc., pp.541-543, 1973 (In Japanese).
11. CHUBU BRANCH, JAPAN SOCIETY OF SOIL ENGINEERING, New Nagoya Geotechnical Graph, 1988 (In Japanese).

Expert System for the Appraisal of Structures
Système expert pour l'évaluation des structures porteuses
Expertensystem zur Beurteilung von Tragwerken

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SUMMARY
The application of a knowledge-based expert system for the appraisal and renovation of existing structures is largely based on the assessment and diagnosis of data obtained from inspections, testing and analysis, and the experience of the structural engineer. The system includes specific information on the durability and causes of age-related problems in structures and has the ability to diagnose inherent problems from test data and visual inspections. The expert knowledge base is controlled by a rule-based logical system utilizing a shell program suitable for use on a personal computer. This illustrates the fundamental concepts and processes of the expert system for the diagnosis of non-structural problems in reinforced concrete.

RÉSUMÉ
L'application d'un système basé sur les connaissances pour l'appréciation et la réhabilitation de structures porteuses est largement fondée sur l'évaluation et le diagnostic des données provenant d'inspections, essais et calculs, ainsi que sur l'expérience accumulée par l'ingénieur. Le système présenté comporte un ensemble de données spécifiques à la durabilité et de causes dues au vieillissement des constructions; il permet de diagnostiquer les désordres à partir des résultats d'essais et des indications d'inspections. La banque de données est contrôlée par un système d'asservissement logique installé sur un ordinateur personnel. Ceci met en lumière les concepts et les procédés fondamentaux du système expert utilisé pour diagnostiquer les problèmes non structuraux dans les ouvrages en béton armé.

ZUSAMMENFASSUNG
Die Anwendung eines wissensbasierenden Systems auf die Sanierung bestehender Bauten fusst weitgehend auf der Einschätzung der Informationen aus Inspektionen, Versuchen und Nachrechnung sowie der Erfahrung des Ingenieurs. Das vorgestellte System enthält spezifische Daten zu Dauerhaftigkeit und Ursachen alterungsbedingter Probleme von Bauten und ist in der Lage, aufgrund von Versuchsergebnissen und Inspektionsangaben zugrundeliegende Schäden zu diagnostizieren. Die Datenbank wird durch ein logisches Regelsystem auf Basis einer PC-gängigen Shell kontrolliert. Ihr Einsatzgebiet sind Gebrauchstüchtigkeitsprobleme im Stahlbetonbau.

1. INTRODUCTION

Outstanding structures have been constructed over many centuries and the corresponding spectrum of materials and techniques used in their design and construction ranges from the forgotten and outmoded to the well tried and tested. Because all structures age and deteriorate a considerable fund of expertise is required to maintain all component parts in a sound and safe condition.

Historic building structures differ widely in configuration, size, condition and usage. Their appraisal has to be methodical and deal scientifically with all the parameters constituting a complete engineering system. Competent engineering judgement is required in each particular case to achieve reasonable levels of public safety.

The basic principles and methods of appraising existing structures are very different from the normal design and analysis of a new structure and the objectives of this expert system is to define these basic principles within a systematic method of approach for carrying out a comprehensive assessment of the condition of an old existing structure, and recommend remedial action.

1.1 Objectives of the Expert System

- In simplest form the Expert System will provide a procedure for guidance on the appraisal system and advice on obtaining more data.
- Provide a systematic approach to testing and instrumentation.
- At more advanced levels an indication of the preservation rating of the structure, and diagnosis of inherent problems.
- Predictions of the future life of the structure and recommended design factors.
- Advice on procedures for appraisal and renovation to inexperienced engineers.
- Provide a comprehensive record of the condition of an old structure in relationship to the history of the structure.

1.2 Scope of the Structural Appraisal Expert System

The purpose of this Expert System is to provide a logic system and a knowledge base to enable the end user to evaluate and recommend a procedure for the refurbishment or preservation of historic structures.

The field of structural appraisal and renovation is very wide and the system described in this paper is restricted to old or historic structures of reinforced concrete or structural steel. Other structural materials such as timber or masonry could be included in the complete system but it is considered preferable that a prototype expert system should first be evaluated and tested before expanding the effort to include other materials.

2. SYSTEMATIC PROCESS OF APPRAISAL

It is essential that a systematic procedure is used to appraise the existing structure which is shown diagrammatically in Fig. 1. The application of Expert Sub-systems is an extension of this procedure and serves as a knowledge-base and guide.

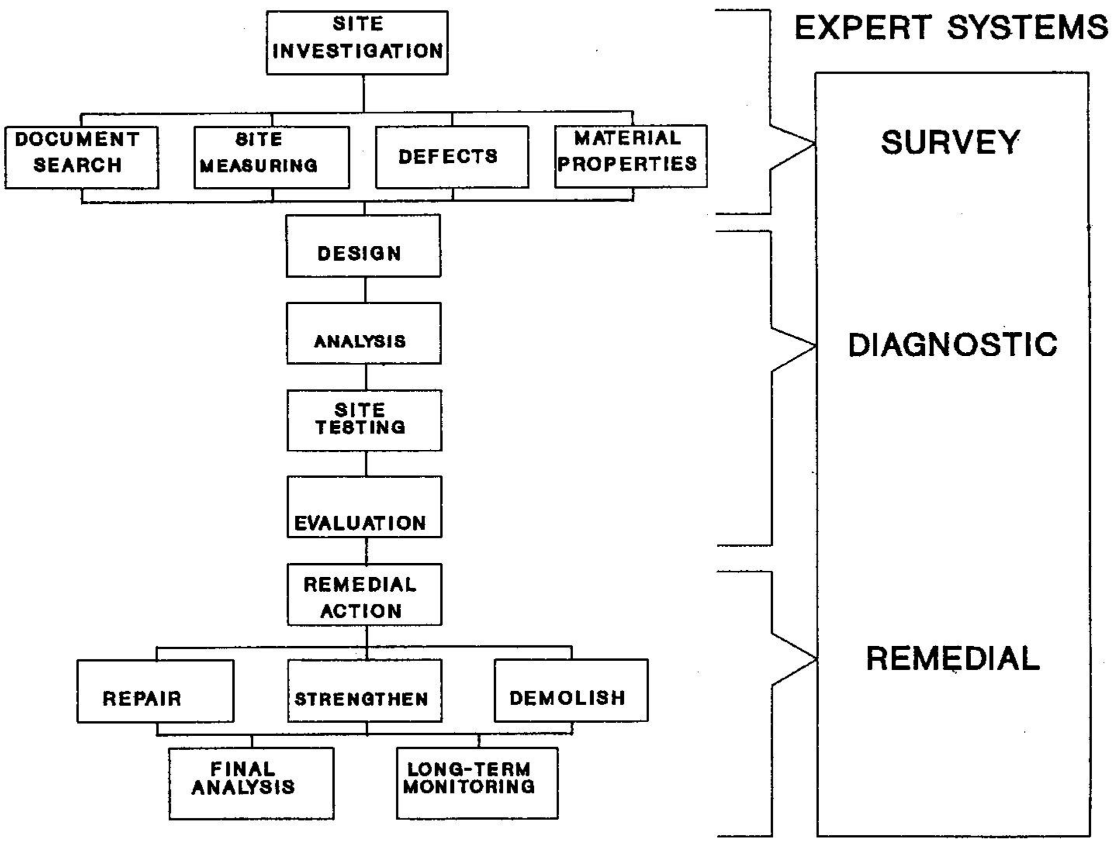

Fig. 1 Process of Appraisal

2.1 Documentation and Archives

An important aspect of any appraisal is the documentation relating to the original design. This would include design, specifications, drawings, calculations and construction records.

2.2 Inspections and Testing

The scope of the survey must include all relevant information about geometry and condition of the structure and materials used in the construction. Specific tests are recommended to determine the degree of deterioration of materials.

2.3 Structural Analysis

This information should be studied and analysed. Checks should be made of the load carrying capacity of the structure and the margins of safety by calculation using the available information on actual loads and the size and strength of the materials and components.

2.4 Forensic Engineering

The definition of forensic engineering used in this system is the investigation of inherent problems in existing structures by means of inspection, survey and testing followed by diagnosis, evaluation, estimation of life-span and repair technology.

The diagnosis of inherent problems in old RC structures is considered in three groups, each of which is a separate Expert Sub-system.

- Structural: This relates to the design and analysis of the structure which give an indication of the state of stress and deformations in the structure under loading.
- Durability: The materials of construction are subject to deterioration with time and the diagnosis of this group of problems is illustrated in more detail as part of the Case Study in Section 4 of this paper.
- Movement: Deformations and subsidence, temperature and creep movements occur in all structures and become evident as a separate group of problems which can be diagnosed.

3. STRUCTURAL APPRAISAL EXPERT SYSTEM

3.1 Modules of a Typical Expert System

The component modules of this Expert System are shown in Fig. 2. The actual system used is the professional version of EXSYS SHELL. Reference [1].

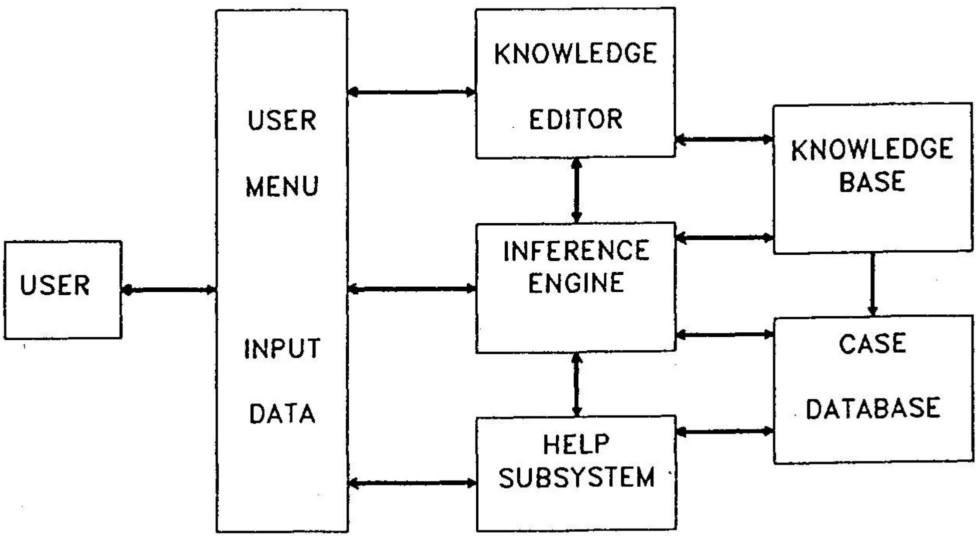

Fig 2. Typical Expert System Modules

3.2 Structure of the Knowledge Based system

Whilst knowledge-based systems differ widely in purpose and capability, they will generally all consist of the following three essential elements:

- The knowledge-base, which contains the data or knowledge that the system utilises. This system is rule-based with forward chaining.
- An inference engine, which provides the mechanism whereby the knowledge base is utilised to solve problems or reach decisions.
- A user interface, allowing the user to provide input and interrogate the system and to receive output in a form that can be used.

3.3 Uncertainty Methods

Three possible methods of dealing with uncertainty have been considered in applying the Expert System to the problem of structural appraisal and these methods from reference [2] are summarised as follows:

3.3.1 Bayesian Probability

Bayes' formula may be used to determine the probability of a given conclusion (C) given certain evidence, or facts (f). The formula is given as:

$$p(C|F) = [p(f|C).p(C)]/p(f)$$

where $p(f) = p(f|C).p(C)+p(f|\sim C).p(\sim C)$
and $p(C|f)$ = probability of conclusion C given facts f
$p(f|C)$ = probability of facts f given conclusion C
$p(f)$ = unconditional probability of facts f
$p(C)$ = unconditional probability of conclusion C
$p(\sim C)$ = unconditional probability of not conclusion C
$p(f|\sim C)$ = probability of facts f given not C

3.3.2 Fuzzy Sets

A set of rules for evaluating a conclusion using fuzzy logic can be provided as follows:

- If premises are connected by the logical AND operator, use the minimum of the fuzzy values associated with the premises to determine the composite value for the premises.
- If premises are connected by the logical OR operator, use the maximum of the fuzzy values associated with the premises to determine the composite value for the premises.
- If the fuzzy value of a premise is given as fv(i) then the logical operator NOT fv(i) = 1 - fv(i).

3.3.3 Exsys Method

The Exsys Shell program permits the use of three different methods for uncertainty. These are as follows

- The 0 to 1 system which refers to absolutely false or true premises only
- The 0 to 10 system which allows for a confidence factor or probability
- The -100 to 100 system is similar to the 0 to 10 system but larger range

4. THE DIAGNOSIS OF NON-STRUCTURAL DURABILITY PROBLEMS IN RC STRUCTURES

The use of an Expert System in the diagnosis of non-structural durability problems in reinforced concrete structures is considered as a sub-system within the general Structural Appraisal Expert System.

4.1 Identification of Major Group of Problems

The first step in this system is to identify the primary non-structural groups of problems which result in corrosion of reinforcement or deterioration of concrete. Although there are many combinations or groups of primary causes of corrosion, this system has been initially restricted to diagnosis of the following four groups:

- Excess Chloride Content (Notation : CHLORIDE = CH)

  The presence of high concentrations of chloride ions migrate to the steel surface and cause a local breakdown in passivity irrespective of whether the concrete is fully alkaline or carbonated, resulting in corrosion of the steel.

- Carbonation of the Cover Concrete (Notation : CARBONATION = CA)

  The effect of carbonation of the concrete is to reduce the concrete pH and change the crystal structure of the cement which leads to corrosion of the steel.

- Inadequate Cover to Reinforcement (Notation : COVER = CO)

  If the cover to the reinforcement is below certain limits and the exposure conditions are severe, corrosion of the steel can occur.

- Alkali Aggregate Reactions (Notation : AAR = AA)

  Alkali-aggregate reaction causes the aggregate particles to expand exerting a bursting force on the localised concrete resulting in map-pattern cracking which can expose the steel to corrosion.

4.2 Identification of Major Symptoms and Test Results

The second step in this diagnostic expert system is to identify the major symptoms or laboratory test results which can identify the primary problem groups as previously defined above. The number of major symptoms has been restricted to eleven for practical purposes and these are grouped as follows:

4.2.1 Visual Symptoms:

	Notation
- Exposure conditions, moisture content, relative humidity	Fm
- Surface texture of concrete, exposed aggregate, porosity	Fs
- Crack Pattern, line cracks, spalling, map-pattern cracking	Fc

4.2.2 On-Site Tests:

- Depth of cover using COVERMETER testing or equivalent	Fo
- Depth of carbonation using PHENOLPHTALEIN testing	Fd
- Crack widths measured by micrometer	Fw
- Electro chemical potential of reinforcement	Fe

4.2.3 Laboratory Tests:

	Notation
- pH value of the concrete cover	Fp
- Chloride content of the concrete	Fh
- Alkali content of the concrete	Fa
- Free expansion tests of core samples	Fx

4.3 Database of Range of Results

The third step in this system is to obtain sufficient data to establish a database of the range of symptoms and test data based on local conditions and grouped according to the risk of corrosion to reinforcement or deterioration of concrete. Part of this database is shown on Table 1. In addition the relative risk factor on a scale of 1 to 9 is indicated. The parameters of Table 1 are primarily based on reference [3].

SYMPTOMS, TESTS	NOTATION	HIGH RISK	RF	MODERATE RISK	RF	LOW RISK	RF
Exposure	Fm	RH > 90%	9	RH 60% - 90%	6	RH < 60%	3
Crack Pattern	Fc	Large, spalling	9	Fine cracks	4	No cracks	1
Cover Depth	Fo	< 10 mm	8	10 - 25 mm	4	> 25 mm	1
Free Carbonation Depth	Fd	< 5 mm	8	5 - 15 mm	4	> 15 mm	1
Crack Width	Fw	> 0.3 mm	8	0.1 - 0.3 mm	5	< 0.1 mm	1
pH Value of Cover	Fp	< 8.0	8	8.0 - 12.0	5	> 12.0	2
Chloride Content	Fh	> 0.6%	8	0.2% - 0.6%	5	< 0.2%	2
Alkali Content	Fa	> 3.8 kg/m3	9	1.8-3.8 kg/m3	4	< 1.8 kg/m3	1
Free Expansion	Fx	> 0.08%	9	0.04% - 0.08%	5	< 0.04%	2

Table 1. Summary of Range of Data related to Risk (RF = Risk Factor)

4.3.1 The key factors which determine the diagnostic knowledge-base are shown on Table 2. and this data is based on local expert opinion in identifying the primary problems. Since certain symptoms or test results have greater significance in the diagnostic process, a weighting factor has been introduced and this shown on Table 2.

DIAGNOSIS		SYMPTOMS or TEST RESULTS								
		Fm	Fc	F0	F2	Fw	Fp	Fh	Fa	Fx
EXCESS CHLORIDES	CH	3 M	2 L	4 H	2 L	2 L	4 H	5 H	2 L	1 L
EXCESS CARBONATION	CA	3 M	2 L	5 H	5 H	2 L	4 H	2 L	2 L	1 L
INADEQUATE COVER	CO	4 H	4 H	5 H	2 L	3 M	4 H	2 L	2 L	1 L
AAR	AA	5 H	4 H	2 L	2 L	2 L	3 M	2 L	4 H	5 H

Table 2. Criteria for Diagnosis (Number = Weighting Factor)
(Letter = Risk Significance, High, Low or Medium)

4.3.2 The derivation of the diagnostic Logic Decision Diagram can be generated through Quinlan's ID3 algorithm which selects the attributes in order of increasing entropy. This decision tree has been based on the data in Tables 1 and 2 and a simplified example is shown on Figure 3.

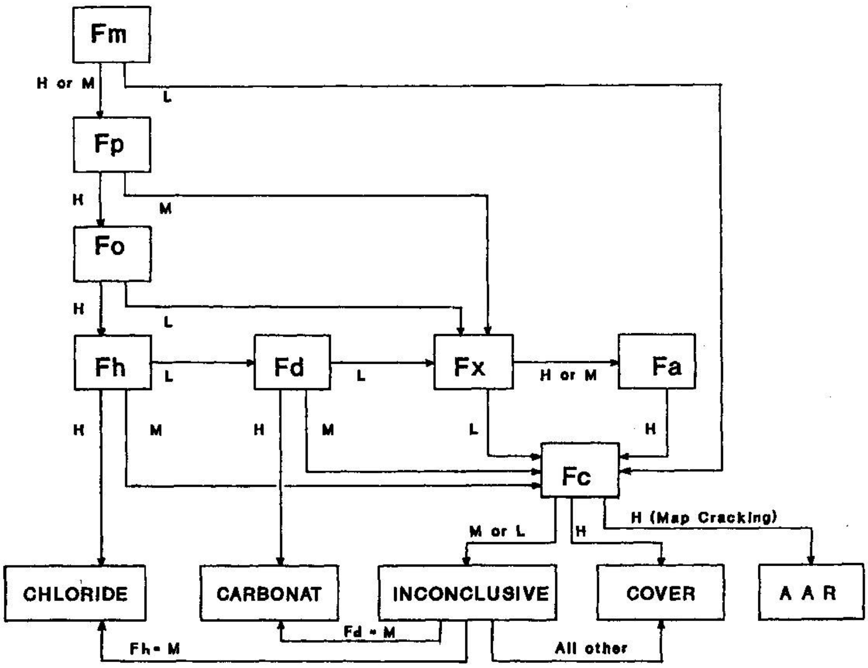

Fig 3. Logic Decision Diagram

4.3.3 The diagnostic system is conditioned to achieving an immediate diagnosis in the case of symptoms or test results which clearly indicate one of the four groups of problems. However, where results are inconclusive the system will evaluate a probability for each of the four possible conclusions and suggest a primary and secondary choice of diagnosis or if insufficient data is available no conclusion will result.

4.4 Development of the Rule-base

The final stages in the development of this system is the Knowledge base which has been determined from the Decision Network. A typical sector of the rule-base attribute-value relationships and confidence factors is given in Table 3.

Rule 1	IF Chloride Content [Fh] > 0.6 AND pH value of Cover [Fp] < 8.0 AND COVER DEPTH [Fo] < 10.0 AND Exposure [Fm] = Normal OR High THEN Diagnosis = Chlorides (Probability = 0.85)
Rule 2	IF Chloride Content [Fh] > 0.2 AND < 0.6 AND pH Value of Cover [Fp] > 8.0 AND < 12.0 AND Core Expansion [Fx] < 0.04 THEN Diagnosis = Chlorides (Probability = 0.55)

Table 3. Typical Example of Rule-base

5. APPLICATION TO CASE STUDY

For validation this diagnostic system has been applied to an existing structure where test data has been obtained and the diagnostic Expert System used to determine the primary causes of steel corrosion and deterioration of the concrete. The details of this case study are given in Tables 4 and 5.

LABORATORY ANALYSIS RESULTS				
		R.C.COLUMN	R.C.BEAM	R.C.SLAB
Exposure conditions	Fm	Exposed Industrial atmosphere	Exposed to Industrial atmosphere	Internal slab, water leakage
Surface texture	Fs	Crack repairs visible	Exposed aggregate	Alkali silica gel present
Crack pattern	Fc	Large cracks spalling	Vertical hairline cracks	Extensive map cracking
Crack width	Fw	0.7 - 1.5 mm	0.1 - 0.3 mm	0.5 - 0.8 mm
Cover meter reading	Fo	Ave 21.3 mm	Ave 8.2 mm	Ave 14.8 mm
pH value of cover	Fp	7.8	12.8	9.3
Chloride content	Fh	0.26%	0.48%	0.15%
Alkali content	Fa	37 kg/m^3	2.4 kg/m^3	7.6 kg/m^3
Expansion of core samples	Fx	0.52 mm/m	0.43 mm/m	0.72 mm/m
Carbonation	Fd	30-35 mm	Ave 5.6 mm	Ave 11.8 mm

Table 4. Data obtained for Case Study for three R.C. Elements of the structure.

DIAGNOSIS	SYMPTOMS or TEST RESULTS FOR R.C. BEAM									Confidence Factor
	Fm	Fs	Fo	Fd	Fw	Fp	Fn	Fa	Fx	
ECCESS	3	3	4	2	2	4	5	2	1	78%
CHLORIDES	7	7	8	6	4	2	7	3	3	
EXCESS	3	3	4	5	2	4	1	2	1	68%
CARBONATION	7	7	8	6	4	2	7	3	3	
INADEQUATE	4	4	5	1	3	4	2	2	1	71%
COVER	7	7	8	6	4	2	7	3	3	
AAR	5	4	2	1	2	3	1	4	5	54%
	7	7	8	6	4	2	7	3	3	

Table 5. Typical Results of Diagnosis for R.C. Beam

(Top Number = Factor representing weighting significance)
(Bottom Number = Factor representing actual test results)
(Confidence Factor calculated using Fuzzy Set methods)

The Confidence Factors indicate that excess chloride is the primary cause of the problem as deduced from the symptoms and test results.

5.1 Conclusion

An Expert System for the structural appraisal of old or historic R.C. structures has been introduced in this paper. The system has been applied to typical elements of an existing structure and this case study has reached the same conclusion as the concrete technology expert.

REFERENCES

1. Professional EXSYS Software Package
2. James P Ignizio., Introduction to Expert Systems - Published McGraw-Hill
3. Fulton's Concrete Technology - Published by P.C.I. Midrand - South Africa

Causal Models and Knowledge Integration in System Monitoring

Modèles et base de connaissances intégrées pour la surveillance

Kausalmodelle und integrierte Wissensbasis für die Ueberwachung

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SUMMARY
In this paper, an expert system is presented that aims to assist engineers in the management of dam safety. The proposed system uses qualitative causal models, hierarchical object-oriented structures, and other knowledge representations linked in an integration environment, for evaluation of data from monitoring and inspections of dams.

RÉSUMÉ
Les auteurs présentent ici un système expert visant à venir en aide aux ingénieurs chargés de gérer la sécurité des barrages. Le système utilise des modèles causaux qualitatifs, des structures hiérarchiques à orientation objet et d'autres représentations de la connaissance liées à un environnement d'intégration. Il permet d'évaluer les données de mesure provenant de la surveillance et de l'inspection des barrages.

ZUSAMMENFASSUNG
Der Beitrag stellt ein Expertensystem vor, das Ingenieuren bei der Beherrschung der Talsperrensicherheit helfen soll. Das System benutzt qualitative Kausalmodelle, objektorientierte hierarchische Strukturen und andere Darstellungen von Wissen in einer integrierenden Umgebung. Es dient der Auswertung von Messwerten aus der Überwachung und Inspektion von Talsperren.

1. INTRODUCTION

This paper derives from a project in progress at ISMES and supported by ENEL/DSR/CRIS that aims to investigate the application of Artificial Intelligence techniques in the field of dam safety.

In order to carry out this task it was necessary develop a conceptual framework within which the techniques of AI could be employed. The approach to dam safety adopted in this project is founded on the view that safety of structures is a problem of continuing management from design through construction to operation and that this management of safety is a quality management procedure (for a more detailed discussion of our view see [2,4]).

AI is seen as contributing to the problem of managing structural safety through providing new methods and approaches to modelling physical systems, such as qualitative physical models (models expressed in non-numerical terms) which can be integrated with conventional engineering models, to provide descriptions of a system at different levels of detail and from different points of view [5]. Knowledge arising from different sources, such as domain theories, codes of practice and experience can be integrated and used to interpret and manipulate on the qualitative and quantitative data of interest [3]. AI environments can provide extensive communication between the user, the models, and the reasoning mechanisms to produce a type of cooperative system of user and machine.

The approach described above to dam safety and the use of AI techniques have led to the design and development of an expert system (DAMSAFE), that uses qualitative causal models, hierarchical object-oriented structures, and other knowledge representations linked in an integration environment, for evaluation of data from monitoring and inspections of dams.

The system harnesses these knowledge structures to evaluate the state of the dam and its near environment through interpretation of these data. The results of this evaluation may be used in making judgements concerning the safety of the structure.

The system may be used in a variety of roles, such as on-line handling of alarms arising from dam monitoring, off-line management of safety of particular dams, assistance in decision making about the allocation of resources in safety improvement programmes, and training of junior safety managers.

2. DAMSAFE

DAMSAFE is a system being developed at ISMES as an environment to implement the approach described above to dam safety, using the tools of artificial intelligence. It is a system in which different types of information (design records, photographs, design drawings, test and monitoring data, qualitative assessments of condition) concerning a dam and different types of models of the dam system (numerical structural models, data models, normative models for behaviour) can be united to assist the engineer in carrying out the procedures of dam safety management. The system provides a platform in which the state of the dam system can be represented and then tested against a variety of normative models. The system is intended as a *cooperative management tool*.

The system developed so far is a prototype that enables hazard audits to be carried out on descriptions of the dam and behaviour of the dam coming from monitoring. The structure of the system is based on three main entities contained within an integration environment:

1. models of the physical world

   These models can be divided into:

   - those which describe the present state of the physical world;
   - those which describe desirable states of the physical world;
   - those which describe undesirable states of the physical world.

   These models are constructed using object-oriented modelling techniques.

2. models of human reasoning (reasoning agents)

   These are models of reasoning about the problem domain, including identification of data features or mapping of data states into dam states.

3. communication mechanisms

   The communication mechanisms take the form of interfacing software components, which enable the user to cooperate with the system through an object-oriented man/machine interface.

The whole system can be used in two different ways:

- as a *diagnostic tool*: there is a sequence of operations of the reasoning agents that allows to translate data into dam states;
- as a *knowledge integrator*: the system assists in the management of safety by facilitating the integration of information about the dam. Drawings, maps and pictures of the dam form part of the information base. Databases of past measurements of the dam can be integrated with the reasoning and modelling system described above. The system functions as an integration tool for different types of knowledge about the dam system, such as theory, regulations and expert knowledge. In such a way the system can be seen as a *virtual expert*, that reflects the knowledge of many different experts (civil engineers, hydrologists, geologists, ...) interviewed during the knowledge elicitation phase of the development process of the system.

3. STRUCTURE OF THE PROTOTYPE SYSTEM

The structure of DAMSAFE is based on the *object-oriented* metaphor. The different types of knowledge represented within the system are integrated using a hierarchical model describing, through objects and attributes, the main components of the system.

The hierarchical structure is comprised of two physical world models and three reasoning agents (figure 1). The *models* make up the problem domain: the *data world* represents all the relevant concepts related to data received from monitoring, while the *dam world* contains all the relevant concepts related to the physical world of the dam. The *reasoning agents* act on the physical world models, and contain the knowledge required to reason about the concepts of these models. They perform a variety of tasks, the most important being that of relating the concepts in the data world to those in the dam system world.

Each model represents a view of the physical world, while each reasoning agent represents a function of the data interpretation process performed by dam safety managers.

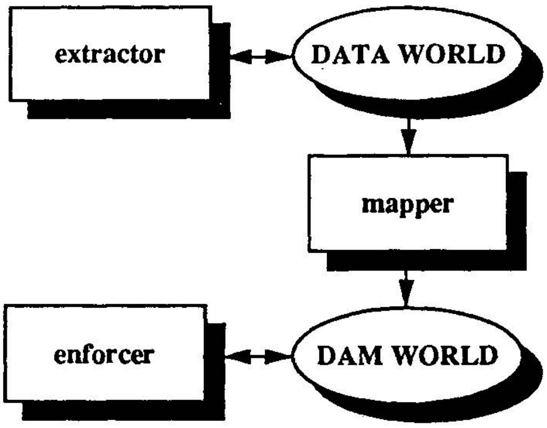

Figure 1: The structure of DAMSAFE

The system is also a data base: attribute values can be saved at the end of a session by using *multiple inheritance* and deriving the attribute to be saved both from a data-object class and from the special *persistent-object* class.

3.1. Data world

The concepts which constitute the data world are those used by engineers in discussing and interpreting the data for dam safety. Some of these concepts are expressed quantitatively, that is, numerically, others are expressed qualitatively. Within this model are the features of data which are significant for identifying particular behaviours and states of the dam system.

Therefore this model contains several *objects*; each of them represents the data related to a single instrument of the monitoring system. These data are *attributes* of the object; they can be time series of instrument readings, as well as details of the type of variable represented. Features such as peaks, trends, steps and plateaux, identified in different types of time series are recorded in this model.

Through the man/machine interface the icon representing the data world can be expanded and the icons representing the objects of the data world appear on the screen. Each object has *methods* to deal with it, which allow the user to access the knowledge linked to the object. In such a way one can read the values of the attributes of the object, or show a time series on the screen. It is also possible to assign values to attributes; this allows the user to act directly on the data world, by-passing the filtering of the reasoning agents.

3.2. Dam world

This world contains a model of the physical world of the dam and its environment, concepts describing the possible states of this world and a set of concepts modelling the possible behaviours of the dam and its environment. The physical dam model describes the dam and its environment as a hierarchy of objects (a hierarchical object-oriented model).

Five objects are currently represented within the prototype: the dam body, the foundation, the curtain wall, the basin, the foundation drains. These objects have attributes which, taken as a set, describe the state of the system. The attributes can be *quantitative* (e.g. the basin level), *qualitative* (e.g. the concrete quality), or *complex* (e.g. the undepressure profile, that is obtained by superimposing the readings of three piezometers to a design drawing of the dam and its foundation, using the representation of the piezometers within the drawing as axes for the measures, and connecting the three points corresponding to the readings on the axes).

3.3. Causal net of processes

The model of the behaviours of the dam system is a set of processes connected in a causal network (figure 2). The causal network models how behaviours of the dam and its environment can interlink in a causal way resulting in scenarios as one process leads to another. The full net includes ninety different processes describing possible dam behaviours. This network has been derived from published case studies of dam failures and accidents, and from discussions with experts in the field of dam design and safety. The conditions under which one process can lead to another have been included. Each of these processes has been documented along with descriptions of how evidence of these processes might be manifested in the monitoring data and also in reports from visual inspections.

The network can be used in different ways:

- as a *data base*: each process has attributes, which describe the process itself (e.g. start time, rate of change, activation state). The system provides methods for accessing such attributes, in order to show to the user their values;
- as a *control panel* of the system: each process is represented on the screen by a box, that is highlighted whenever the system infers that the process is active. Therefore the highlighted boxes give to the user an immediate synthetic report on the current state of the dam. Besides the activation state, other attributes (reversibility, speed) are represented by coloured areas of the box linked to the process representation on the screen;
- as an *inference tool*: the causal links can be used by automatic reasoners for building paths of events to be used for simulating the future evolution of the system state or identifying the possible causes of an active process;
- as a *knowledge base*: each process is linked in a hypertextual way to its written documentation, that describes the process and its connections to other entities (processes and objects). Therefore the theoretical foundations of the system itself can easily accessed through the user interface.

3.4. Reasoning Agents

Three reasoning agents were designed, and the first two have been fully implemented, while the third one is under development.

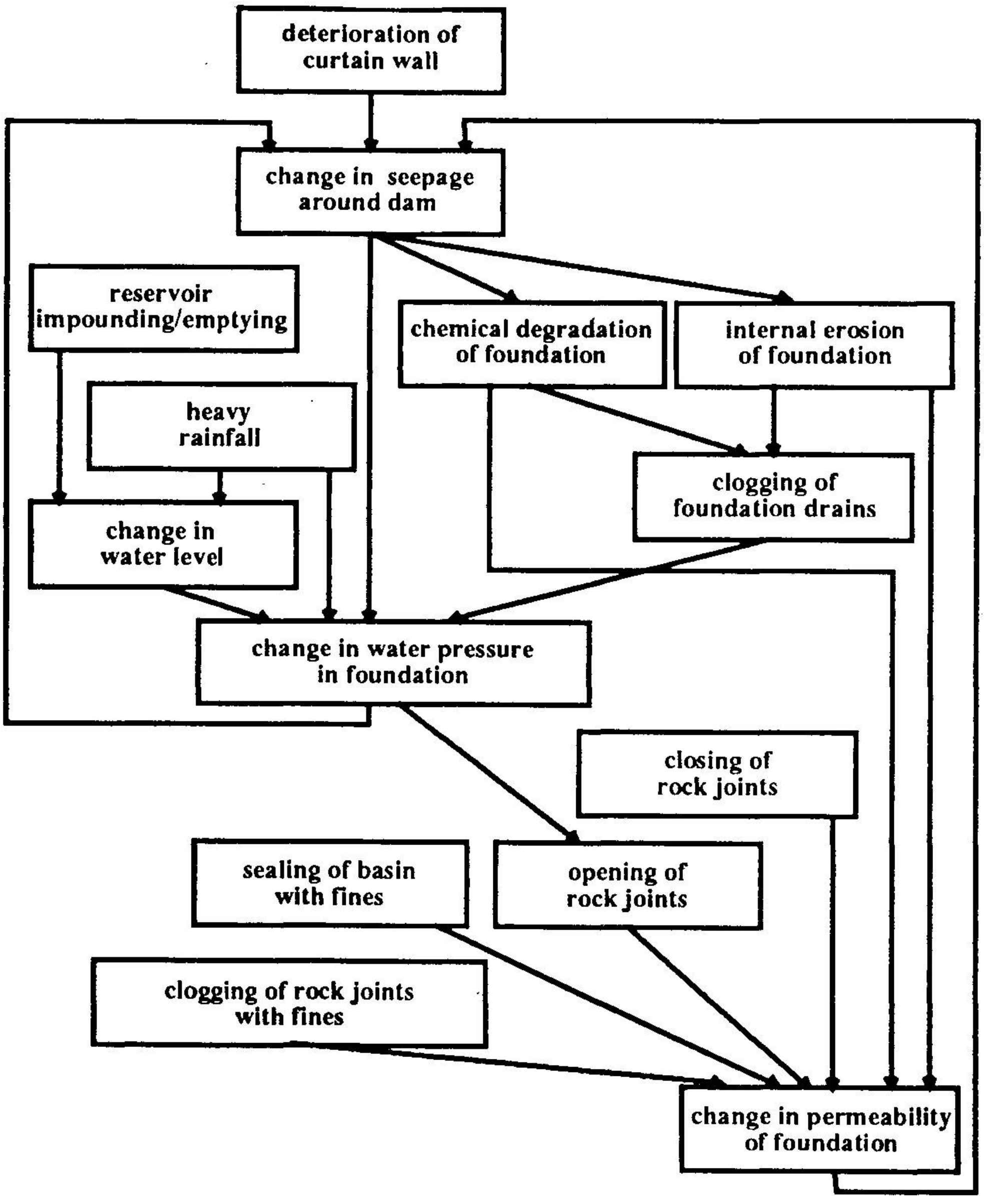

Figure 2: A section of the causal network of dam behaviours

The first one (extractor) operates solely on the data world to manipulate the data and extract features from the data sets of importance. It uses the graphical interface to show to the user a time series plot and to interactively find out a set of *features* of the plot which are considered relevant to dam safety. Possible features are trends, spikes, steps and plateaux. They are defined by qualitative and quantitative attributes (e.g. spike length, start time) and stored within the data world. These attributes can also be accessed and manipulated through methods of the data world, which may be considered as data base management utilities.

The second reasoning agent (mapper) performs the task of interpretation identifying both the possible behaviours of the dam in terms of a set of processes in the causal net, and the values of various attributes of the dam, based on evidence in the data.

This task is performed by firing *rules* defined by experts, which link data values to dam states (see table 1). These links are defined by using a formal language designed with the aim of allowing non-programmers to easily write and read rules (see table 2). The rules are translated into C++ code, compiled and then executed by the mapper. A rule is fired if a *precondition* on the values of some data world attributes is verified; in this case, the state of some dam world process is declared active and some dam world attributes receive a value. The set of active processes linked in a causal chain are highlighted by the system and describe a scenario that demonstrates the evolution of the dam behaviour.

The third reasoning agent (enforcer) acts on the dam world to extend the implications of the state identified by reasoning agent 2, over the model of the dam and its environment thus highlighting possible causal chains.

Once a model has been built of the state of the dam system in terms of a set of active processes (behaviours) and a set of attributes, this state can be tested against normative models to make judgements about the safety of the dam

4. APPLICATIONS OF THE SYSTEM

The system is aimed to be general in that it may be used (in different forms) off line to assist in investigations of safety or for training, and also on line for the generation of warnings at the dam site through interpretation of automatic measurements. The system is a decision support system and in that sense does not provide answers but assists the engineers to manage the problem. It is cooperative and interactive drawing on the relative strengths of man and machine to manage the information for safety of dams. Because of the hypertextual nature of the on-line documentation, the system can be used as a training tool for junior engineers.

An off-line version of the system is currently under validation at ISMES by dam safety experts (figure 3). It was developed on Sun workstation platforms using C++ and the InterViews toolkit of the X Window System. The system consists of about 100,000 lines of source code.

A neural network based tool was developed for supporting the feature extraction process from data and is going to be integrated with the main programme ([1]).

An on-line version of the system was developed and installed on a concrete dam in order to filter, evaluate and explain alarms coming from an automatic monitoring system; this on-line version of DAMSAFE performs a subset of the functionalities designed for the main system, since it deals only with single readings of the monitoring instruments and is able to identify a restricted set of possible processes ([6]). This system runs on a PC under MS-Windows. Both the evaluator and the explainer are written in Prolog, while the communication mechanisms with the monitoring system, the internal data base manager and the interface are written in Microsoft Visual Basic.

5. ACKNOWLEDGEMENTS

We would like to thank the people that implemented DAMSAFE: Mauro Cadei, Marino Rocca, Marco Testa, Luca Ceri, Flavio Raimondi, Paolo Sergi and Matteo Vaccari.

6. REFERENCES

1. BIELLA, G., *Analisi mediante reti neurali di segnali provenienti da sistemi di monitoraggio in ingegneria civile.* Thesis, Univ. of Milano, 1992.
2. COMERFORD, J.B. and D.I. BLOCKLEY, Managing safety and hazard through dependability. *Journal of Structural Safety,* (In Press)
3. COMERFORD, J.B., M. LAZZARI, D. PINA, and P. SALVANESCHI, An AI approach to the integration of engineering knowledge: water resources case studies. *Proc. of AIENG 92: 7th Int. Conf. on Applications of Artificial Intelligence in Engineering,* Univ. of Waterloo, Ontario, July 1992.
4. COMERFORD, J.B., P. SALVANESCHI, M. LAZZARI, P. BONALDI, G. RUGGERI, M. FANELLI, G. GIUSEPPETTI, and G. MAZZÀ, The role of AI technology in management of dam safety: the DAMSAFE system. *Dam Engineering,* **3**(4), 1992.
5. COMERFORD, J.B. and J.R. STONE, Artificial intelligence in risk control. In D.I. Blockley (Ed.), *Engineering Safety*, McGraw Hill, London, 1992.
6. LAZZARI, M. and P. SALVANESCHI, *MISTRAL - An expert system for the management of warnings from automatic monitoring systems of dams.* Internal Report, ISMES, Bergamo, 1992.

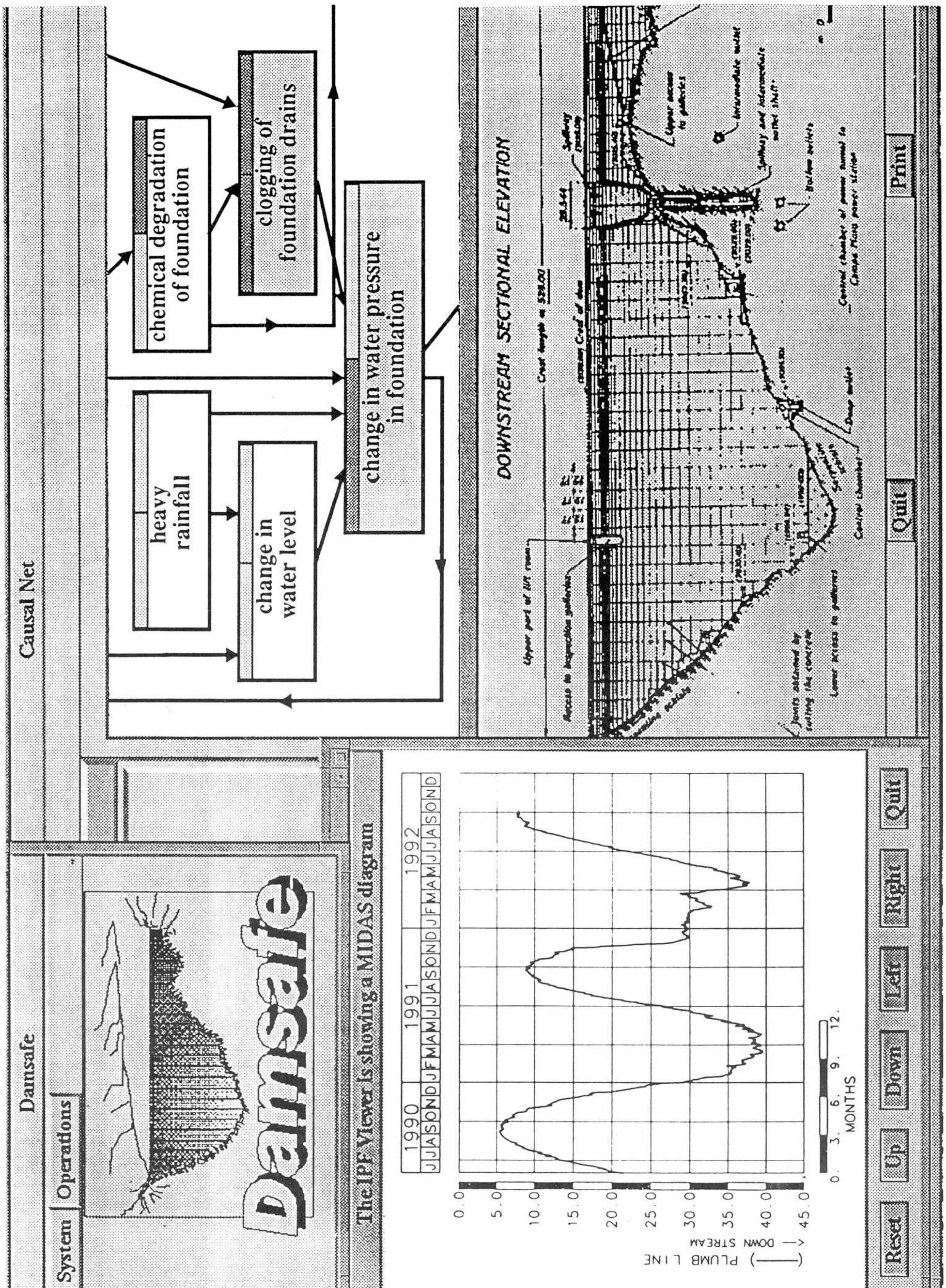

Figure 3: Information representation in DAMSAFE

```
Rule_4(
  CONDITION(Trend OF UnderseepageTimeSeries);
  ASSERT    (ChangeInSeepageAroundDam),
  SET       (
            StartTime OF ChangeInSeepageAroundDam
              TO StartTime OF Trend OF UnderseepageTimeSeries
            AND
            FinishTime OF ChangeInSeepageAroundDam
              TO FinishTime OF Trend OF UnderseepageTimeSeries
            AND
            ProcessSpeed OF ChangeInSeepageAroundDam TO "slow"
            ),
  MAP       (
            Gradient OF Trend OF UnderseepageTimeSeries
            INTO
            RateOfChange OF ChangeInSeepageAroundDam
            )
  )
```

Table 1: A rule of the mapper

```
<ANiceRule> ::
  (
   CONDITION( <Condition> ),
   ASSERT( <ListOfDamProcesses> ),
   SET( <SetList> ),
   MAP( <MapList> )
  )

<Condition> ::
 <ExistentialCondition> | <RelationalCondition>

<ExistentialCondition> ::
 <ListOfFeatures>

<ListOfFeatures> ::
 <Feature> OF <DataObject> [ OR <ListOfFeatures> ]
```

Table 2: A part of the grammar of the rule-based language used by the mapper

Structural Damage State Assessment via Neural Networks

Détermination des dommages à l'aide de réseaux neuronaux

Bestimmung von Tragwerksschäden über neuronale Netzwerke

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SUMMARY
This paper presents experiences in the implementation and use of neural networks aimed at a novel approach for detecting and characterising faults and other nonlinear mechanisms related to defects or damage in civil engineering structures. Fundamental aspects are addressed and discussed, such as learning stategies, network organisation-topology, error and convergence characteristics, normalisation procedures. While preliminary in nature, the results obtained show a considerable potential in the neural network approach, together with a number of open problems and with indications for future research lines.

RÉSUMÉ
L'article traite des expériences faites par la mise en application et l'utilisation des réseaux neuronaux, en vue d'une nouvelle approche pour la détection et la caractérisation de défauts et d'autres mécanismes non linéaires en liaison avec des dommages dans les ouvrages de génie civil. La discussion porte sur certains aspects fondamentaux du problème, comme les stratégies d'apprentissage, la topologie de l'organisation des réseaux, les erreurs et les caractéristiques de convergence ainsi que les procédures de normalisation. Les résultats obtenus jusqu'ici montrent les énormes possibilités offertes par cette méthode, mais également un certain nombre de problèmes restant en suspens et des indications relatives aux objectifs de la recherche future.

ZUSAMMENFASSUNG
Der Beitrag berichtet von Erfahrungen mit der Implementierung und Anwendung neuronaler Netzwerke bei der Entdeckung und Charakterisierung von Fehlstellen und anderer nicht-linearer Mechanismen infolge von Schäden im Ingenieurtragwerk. An grundliegenden Gesichtspunkten werden die Lernstrategien, die Topologie der Netzwerkorganisation, Fehler- und Konvergenzeigenschaften sowie Normierungsverfahren behandelt. Vorläufige Ergebnisse zeigen für diese Methode beträchtliche Möglichkeiten auf, aber auch ungelöste Probleme und die Richtung zukünftiger Forschung.

1. INTRODUCTION

Repair and retrofitting of existing structures and infrastructures is in steady growth in the whole world, due to their increasing service life, as well as to the deterioration arising from accelerated loading and aggressive environments. Procedures which can improve reliability and prediction capability in these areas would be of major benefit to the technical community. The work presented is part of a research project directed toward the development and application of neural networks as a novel approach for detecting and characterising faults and other nonlinear mechanisms related to defects or damage in civil engineering structures. Fundamental aspects are addressed and discussed, such as learning strategies, network organisation-topology, error and convergence characteristics, normalisation procedures. The dynamic response of structures, comprising artificial signals from numerical models, experimental signals from laboratory tests and some examples on full scale structures, is adopted as network input. Mechanisms examined are the opening-closure of gaps (cracks) and the presence of nonviscous dissipation, including friction and hysteresis.

2. THE NEURAL NETWORK APPROACH

2.1 Generalities on Neural Networks

Without intending to provide a full discussion, well available in the many books and papers on the subject, see e.g. [1,2], a synthetic information shall be given for the unacquainted reader. Artificial neural networks are computational systems, composed of elements (the artificial neurons) that perform in a manner analogous to the most elementary functions of the biological neuron. Their birth in the present acceptation can be indeed traced to a fundamental work of Hebb, [3], showing how a neuron network could exhibit a learning behaviour. A neural network amounts to a highly interconnected system of artificial neurons arranged in layers, the first and last of which are respectively the input and output layers, while the intermediate ones are called hidden layers, see Fig. 1. The preliminary and fundamental phase of their use is that of *training*, in which a set of input patterns, representative of a specific phenomenon, is fed in and the processing algorithm in the hidden layers is tuned until each pattern matches to a required accuracy a given set of outputs. Once the network is trained, its use takes place feeding the input layer with new data, often called *test patterns*, selected within the same class of phenomena of the training phase, but different from the training ones: the output provides an estimate of the same kind of answers aimed at in training.

Such two-step procedure exploits many positive features. In training the net "learns" from experience, accumulates "knowledge" and it is "sensitive" to the environment. Furthermore, its response can be, to a degree, insensitive to input changes, resulting in "generalisation", i.e. in the capability of abstracting the essential features of a set of inputs. They are hence ideally suited to cope with systems affected by noise or distortion and with fuzzy problems in general. Note that a net generalises as a result of its structure and not by use of embedded artificial intelligence, a concept completely absent in its rationale. For system identification, the most attractive property is the potential to reproduce the behaviour of input-output systems, yielding non parametric black-box representations. This implies that no knowledge of the underlying physics is necessary, but no related information is obtained either. Such properties caused in the last decade a burst of activities, with theoretical developments and applications in heterogeneous fields, whenever parametric models were too demanding, if non impossible. Despite such accomplishments, it must be borne in mind that neural networks are simply a new curve-surface fitting algorithm, producing no more than a powerful and flexible multi-dimensional polynomial interpolation method. Their use should hence be strongly connected to the knowledge of the underlying algorithms, as well as to the understanding of potential and limits.

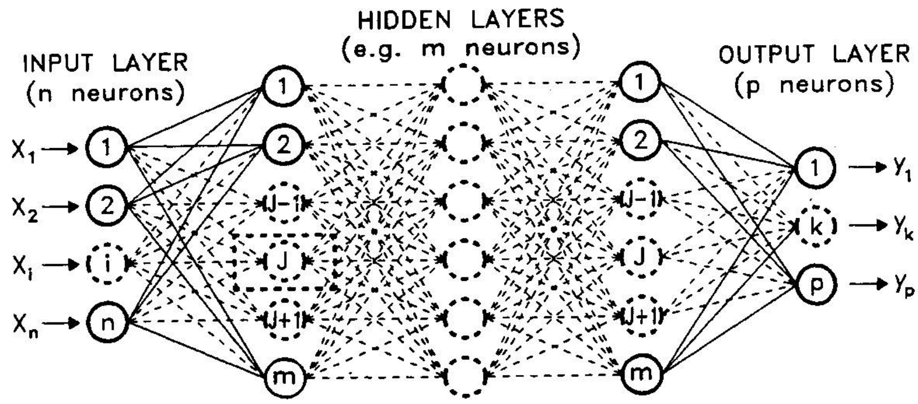

Fig. 1 Typical network structure

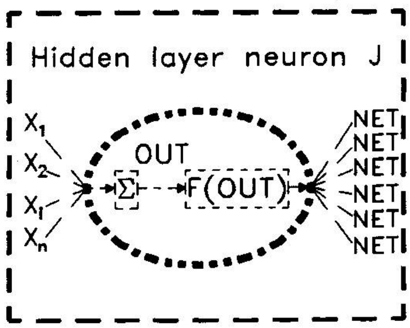

Fig. 2 Basic MLP neuron

2.2 Fundamentals of Multi-Layer Perceptron Back-Propagation (MLP) Networks

Multi-Layered Perceptron Back-Propagation (MLP) networks are adopted here [1,4,5,6,7]. They revealed in the last years the most reliable, becoming the present established state-of-the-art technique in the field. Earlier perceptrons were severely limited in what they could represent [13], until the development of back-propagation [5,6,7] led to practicable MLP's with any number of layers. The fundamental building block for an MLP is the *artificial neuron*, whose scheme is shown in fig. 2. The X_i are the inputs received from the previous layer neurons, to each of which it is assigned a weight. For each neuron a summation produces the term NET, subsequently modified trough an *activation function* F to yield the neuron output OUT. Commonly used are the sigmoidal function, adopted here, or the hyperbolic tangent, as they both show several useful features: i) they restrict the output between 0 and 1; ii) they have a simple continuous derivative; iii) they add automatic gain control, as for small input their derivative is high, while for large ones reduces progressively: this avoids saturation and attenuation. For MLP's, the phase of training becomes a process aimed at adjusting the neuron weights so that the application of a given input pattern, defined as a vector, produces the desired output, also in vector form. This is done via the already described procedure, called *forward pass*, and a subsequent *reverse pass*, in which the weight adjustment takes actually place.

Despite their success, MLP's have serious limitations in both application and implementation. A primary disadvantage is connected to the use of a steepest descent procedure, ensuring convergence to a minimum, but not to the absolute one. Second, there is no theoretical guide as to what the best stepsize should be. The convergence proof assumes infinitesimal weight adjustments, i.e. infinite training time: stepsizes can hence be assessed only through experience in each application field. This may lead to the need of a very large number of iterations to converge. On the other hand, a stepsize too large may cause solution divergence, paralysis or instability. This explains the interest in the development of innovative, more powerful and more reliable network concepts, to which a large research effort is being devoted worldwide [4,8,9,10,11,12].

2.3 Scope of Work

Most industrial applications of neural networks in engineering lay within Electronics and Control, and more recently also in Mechanical Engineering. At a research or pre-industrial stage, some excellent proposals are concerned with nonlinear systems identification [13,14,15,16], while fewer are devoted to structural fault detection [17,18]. In Civil Engineering, the authors are aware only of the rather questionable work [20], besides those within the European Community NEWNET project [21,22], to which the present belongs. To clarify the scope of this work, one must remeber that networks can *detect*, *predict*, *localise*, *classify* or *quantify* relevant phenomena. Cases of classification and quantification are presented here. A second decision area concerns the type of information to feed as input pattern, which should take the form most appropriate to allow the extraction of significant *features* of the phenomena in consideration. First, signals may derive from the raw or processed structural response. Processing may take place in the frequency domain, with first or higher order spectra [23], or in the time domain, e.g. through Hilbert transforms [24], or even in the time-frequency space [24]. In the frequency domain the typical input should be a sinusoidal excitation, leading to frequency response functions (FRF). As the final goal of this approach is the use on civil engineering structures, typically subjected to sinusoidal forces only through external devices which might limit operation and are often unwelcome, the practical use of FRF's is limited. Much more interesting are the free oscillations, with impulse response functions (IRF), or the excitation through random loads, including operational or environmental actions. This work is concerned with IRF only, i.e. with a free oscillation response network input. Furthermore, the free response can be represented via different variables, in the displacement or in the force domain. Here the displacement response is considered; however, this does not imply a preference indication, not yet mature. Within the above, a few more aspects must be discussed. First, signals including noise, generated via one d.o.f. numerical models, are used; this provides an assessment of the possibility of training networks on artificial signals, easily generated in large quantities, rather than on experimental ones. The limitations connected with the single d.o.f. training are well understood and the extension to multi d.o.f. systems shall be a natural prosecution of this work. Second, a very simple input, comprising only a single oscillation wave is used for training; also this aspect is considered of significance, as it tests the nets in conditions in which standard identification procedures are not easily applied and because in real applications one is often faced with scanty or short recordings.

3. MLP NETWORKS FOR PROPERTY CLASSIFICATION

3.1 Preliminary Remarks

Experiences in implementing networks as classifiers of mechanical systems properties are presented. For classification, the typical neuron output sought is binary: for each class it is provided one neuron, with a 1 or 0 output to stand for positive or negative answer. Two cases shall be discussed, concerning energy dissipation type selection and nonlinearity discrimination.

3.2 Characterising Energy Dissipation

Dissipation mechanisms considereded are: i) linear viscous damping; ii) dry friction; iii) hysteresis, with elastic-perfectly plastic constitutive law. Hence, the output layer comprises 3 neurons, trained to produce the 0-1 (No/Yes) binary output. Training was carried out on single waves, described from zero to zero through 21 time stations, resulting in a 21 neurons input layer, with different levels of white noise added. The dissipation rate selected was such that from 1 to 10 % of energy is lost in one cycle. Several topologies were considered, with 1 to 3 hidden layers and 4 to 21 neurons per layer: in general the performances were quite uniform, with a marginal improvement for larger and multi-layer schemes. No particular difficulties were observed in training: while a binary response was considered reliable when affected by an absolute error below 10^{-2}, the typical accuracy achieved was of the order of 10^{-4}. Only aspect worth mentioning is the necessity, to avoid excessive training time, of an analyst-monitored tuning of the back-propagation step. The real test of the reliability and generalising capabilities of a net is not a successful training, but its performance on other signals, not used in learning and hence "unknown". Once trained, the nets were used on a large set of test patterns, including i) signals belonging to the training classes (i.e. viscous damping, friction or hysteresis) and inside the training range (i.e. 1 to 10 % energy loss per cycle); ii) signals within the training class, but outside the training range (from 0 to 1 % or from 10 to 20 % energy loss per cycle); iii) signals of other nature, not belonging at all to the training mechanisms. The latter comprised white noises, oscillations to which a large noise was superimposed, multi-d.o.f. systems and other functions, among which to notice also elastic undamped oscillations. The results are summarised in Table 1, for some of the nets considered. A response was defined "true" when only the correct neuron was activated, with an error on the binary output below 0.02 (twice the accepted training error). On the contrary, it was defined as "uncertain" if more than one neuron was activated or if the error was over 0.02, and finally "false" if only one wrong neuron was activated, with an error below 0.02. First useful outcome, the network classification was always 100 % correct for patterns within the training classes and range (A rows in Table 1). When applied to signals within the training classes, but outside the training range (B rows), the results were still favourable, with a true response average of 70 %. For other signals (C rows), an unfavourable aspect showed: a majority of false answers. This stresses a trend, typical of simpler neural networks, to yield an answer anyhow, even for meaningless input. One must note that while an uncertain answer is acceptable, as it introduces a doubt element in the identification, nothing is worse than a clear, sharp, wrong response, specially dangerous when the class and range of the signals analysed is not easily determined in advance. To cope with such *false answers*, for the training classes the best measure is to extend, within reason, the training range, while for "other signals" one should use networks capable of their exclusion. As this is at present beyond the possibilities of existing algorithms, a chance lies in adding in training samples of signals to be refused, activating an "else" neuron. This was done appending 15 further such inputs, with the results shown in Table 2: the improvement is evident, with a massive decrease of false answers, despite the comparatively small training set. This underlines a potential in the approach, but industrial-professional use would require a larger and improved training, seeking a greater reliability. To note that in this case training small single-layer nets was unsuccessful and, even when achieved, two-layer ones performed better.

3.3 Damage Detection in a Coupled Mechanism

This example is concerned with the capability to discriminate a linear from a nonlinear response. The second is represented by a bi-linear stiffness constitutive law, typical of a gap or crack opening-closure phenomenon in a structural element. To make the identification more challenging, the nonlinearity level adopted was quite mild, with a stiffness variation from 0 to 10 %, and both the linear and nonlinear cases were coupled to a rather large viscous damping, with critical ratio from 0 to 0.1. The results obtained with a single-layer, 5 hidden nodes net were even more accurate than in the previous case. Not only the binary test patterns classification was 100 % correct within the training range, but also well outside, for damping ratios up to 0.2 and stiffness reduction up to 20 %. Beyond, the response deteriorated progressively but slowly, keeping a large percentage of true answers. This is specially interesting as, with the poor information provided, standard methods would not achieve the same, in particular for high damping, small nonlinearity cases, where the dissipation "cancels" most of the bi-linear oscillator response features.

4. MLP NETWORKS FOR PARAMETER QUANTIFICATION

4.1 Preliminary Remarks

In a first stage, it was attempted to implement quantifiers as an extension of classifiers, replacing the yes/no output with a numerical one. This line did not fail completely, but showed not very effective. After some effort, it was concluded that quantification could be accurate only if carried out on its own,

Network Topology		Network output (%)		
		True	Unc.	False
21-4-3	A	100	0	0
	B	73	18	9
	C	0	49	51
21-6-3	A	100	0	0
	B	64	12	12
	C	0	48	52
21-10-3	A	100	0	0
	B	72	17	11
	C	0	53	47
21-21-3	A	100	0	0
	B	75	16	9
	C	0	42	58
21-4-4-3	A	100	0	0
	B	67	12	11
	C	0	2	98
21-8-8-3	A	100	0	0
	B	74	16	10
	C	0	36	64
21-12-12-3	A	100	0	0
	B	76	16	8
	C	0	46	54

Table 1 Response for test patterns of energy dissipation classifiers without "other signals" option

Network Topology		Network output (%)		
		True	Unc.	False
21-10-4	A	100	0	0
	B	67	26	7
	C	49	37	14
21-4-4-4	A	100	0	0
	B	72	15	13
	C	75	10	15
21-12-12-4	A	100	0	0
	B	73	21	6
	C	75	19	6

A = Test patterns within training class and training range

B = Test patterns within training class but outside training range

C = Test patterns outside training class and range (unknown signals)

Table 2 Response for test patterns of energy dissipation classifiers with "other signals" option

aiming at one parameter at a time. Hence, the nets adopted have only one output neuron, yielding the scaled parameter value. As to topology, small single-layer nets proved effective; all the results presented were obtained with 21-5-1 schemes. An other general conclusion reached was that quantification might be effective only within the training range, while the distortion outside causes large errors, with lesser generalisation capabilities.

4.2 Rating Stiffness Nonlinearity

Reaching a high accuracy is here much more important than in quantification and proved correspondingly harder. This first example quantifies the stiffness variation from the response of the bi-linear oscillator treated in 3.3. The variation range is 0-10 %, with the net output indicating the stiffness ratio, from 1 to 0.9, and the training set comprising only 5 patterns.

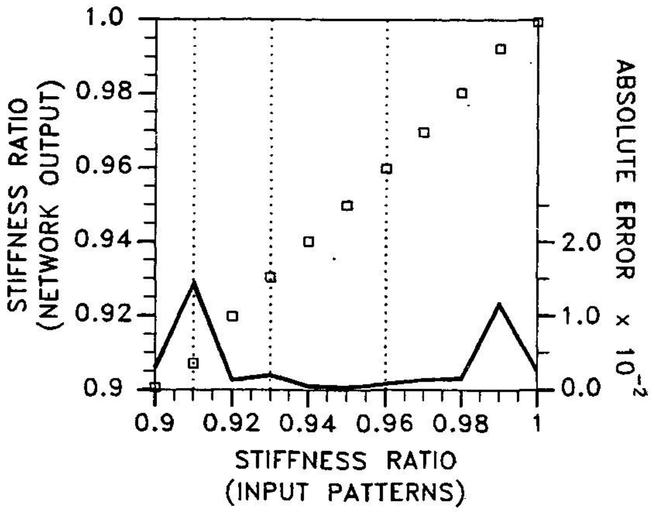

Fig. 3 Rating stiffness nonlinearity

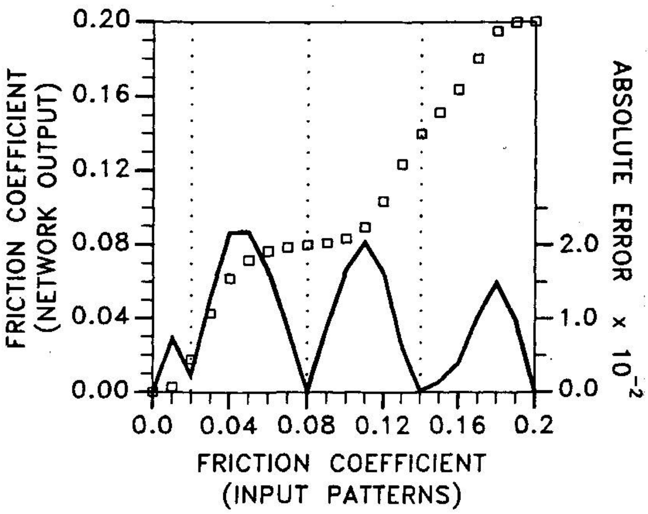

Fig. 4 Rating friction coefficient

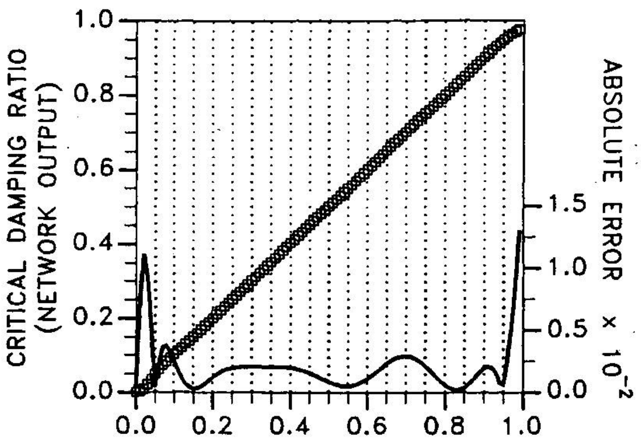

Fig. 5 Rating critical damping ratios in the 0-1 range

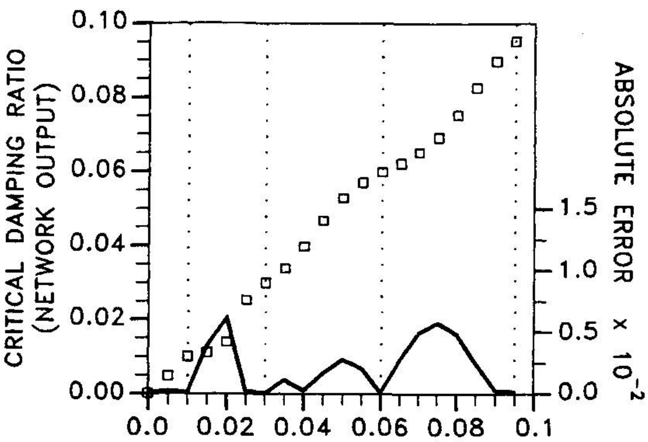

Fig. 6 Rating critical damping ratios in the 0-0.1 range

The results are shown in fig. 3: the boxes represent points in a correct response-net response plane for the test patterns, hence with a perfect output producing a straight line with $\pi/4$ slope. The error for each case is also superimposed in a solid line, while vertical dots indicate the training patterns locations. Reaching in training quite good accuracy, with absolute errors of the order of 1×10^{-3} proved not too difficult, but when the net was applied to test patterns the errors were one order of magnitude larger, with typical peaks at the training range edges. To improve the results, a first direction followed was the improvement of the training accuracy: consequences are shown with the next examples, aimed at energy dissipation mechanisms rating.

4.3 Rating Energy Dissipation Mechanisms

The first case shown concerns the quantification of the dry friction coefficient, treated with a net scheme analogous to the previous one. As anticipated, a better training accuracy was sought. This proved quite difficult, requiring higher weight momenta [4], sharper activation functions and careful supervising of back-propagation step, with greater instability liability. Nevertheless, accuracy was improved, with errors form 10^{-4} to 10^{-5}. Though, this proved a failure, yielding the results exemplified in fig. 4, with even lower accuracy for test patterns and characteristic error peaks between training points. Such behaviour is well known to be peculiar of neural networks, as very accurate reproduction of training points might imply a more uneven solution in terms of the polynomial approximation in the neuron output space. This underlines an aspect which is fundamental in network applications: the real and challenging target is not just to obtain an excellent training, but to generalise, keeping an elevate accuracy for unknown signals in the training class. From this point of view the guidance given by the theory, scarce also within the training procedure, is virtually absent and only experience might help. To improve the performances, an obvious measure is the increase of the training patterns number, as exemplified in fig. 5 with a network which quantifies viscous damping ratios in the 0-1 range, for which 20 patterns were used. The error is satisfactorily low for most of the range, but the peaks at the edges. Further improvements might be obtained specialising the net in narrower ranges, e.g. for 0 to 0.1 damping ratios, as in fig. 6, but error peaks are still present. Better result were achieved optimising the training points location and, more important, seeking training strategies yielding uniform error levels. This was successfully achieved with smooth activation functions and comparatively short steps, yielding very slow training. The quality attained is shown in fig. 7, for the quantification of yield ratios in elastic-perfectly plastic oscillators, where with only five training patterns the accuracy is uniformly of the order of 10^{-3}.

5. PERFORMANCES FOR EXPERIMENTAL SIGNALS

5.1 Laboratory Tests

To progress towards site applications, it has been started an experimental laboratory program, whose first specimen is a simply supported, 5 m long I steel beam, set with horizontal web and ballasted to obtain the desired frequency range, fig. 8. IRF responses have been recorded in some of the conditions examined previously, i.e.: i) linear oscillations; ii) friction, obtained by purposeful tightening of one support roller; iii) bi-linear stiffness, obtained trough an artificial crack at midspan. Several probes were placed on the specimen; the results presented refer to displacement transducers response.

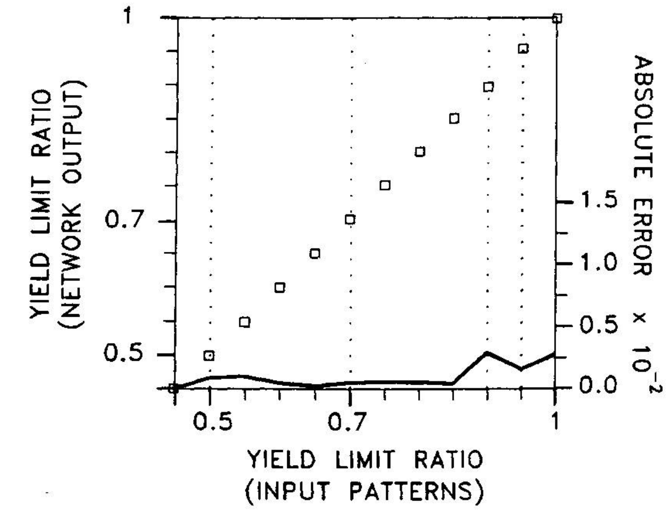

Fig. 7 Rating yield limit ratios

For the nonlinearity aspect, the net performances were satisfactory, considered its early development stage: the classification network described in 3.3 discriminated correctly the damaged-undamaged beam oscillations, while the quantification network of which in 4.2 rated the stiffness ratio of the bilinear constitutive law in 0.94. The theoretical design value, obtained through f.e. analyses, was 0.96, with an experimental value from static test, considered the most reliable, of 0.95. Further identifications from the dynamic response, via time domain Hilbert transforms [24], yielded values between 0.95 and 0.97.

Somewhat inferior were the results for the energy quantification field. The classifier indicated always correctly the presence of linear damping only, while its quantification was poorer, due to its very low value. The net rating was 0.0059, with exact values from envelope curves via Hilbert transforms of 0.0029. Note that the latter were obtained from a much richer information, i.e. the full recorded signal and not just a single wave. In fact, improvements, not reported as they are outside the scope of this paper, have already been obtained training the net on longer signals. When applied to friction identification, the classification was less reliable, though with a majority of true answers, and also inaccurate resulted the quantification. This is still being studied: a possible cause is considered the lack of symmetry of friction forces, introduced in one support only, with significant introduction of higher modes contribution.

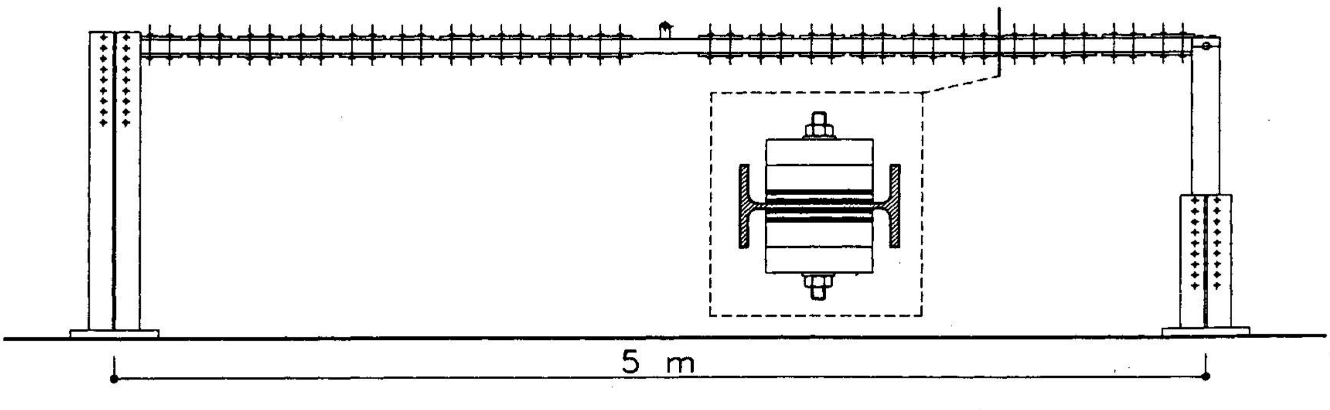

Fig. 8 Steel I beam experimental specimen

5.2 Full Scale Structures

For the sake of completeness, also some preliminary applications on real structures are presented, regarding a number of multi-span (31 m), simply supported, prestressed concrete viaducts, with the cross section shown in fig. 9, located on the A3 motorway in southern Italy. The dynamic tests, carried out during operation, were part of a retrofitting program.

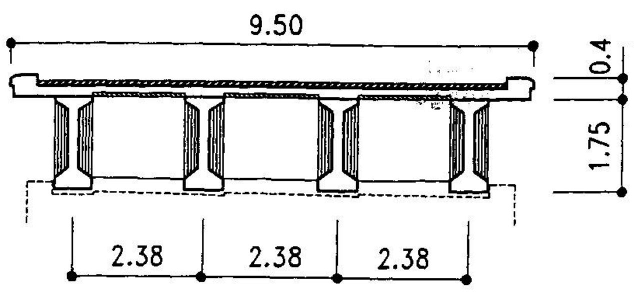

Fig. 9 Bridges cross-section

As the recording had been already analysed via standard identification methods, it was known that the response was characterised by the coupling of flexural and torsional modes and a modal filter had already been developed [24], to obtain single mode contributions for the treatment via Hilbert transforms, that were fed to the nets, aiming at linear damping quantification only. The critical ratios obtained from the networks for five recording samples were 0.015, 0.019, 0.016, 0.017, 0.048; standard processing procedures indicated for the same cases values of 0.018, 0.020, 0.013, 0.017, 0.047, with a very satisfactory correspondence, also considering the scattering of the original signals.

6. CONCLUSIONS

The experiences presented, though preliminary in nature and limited in scope, have shown a considerable potential in the neural network approach, which proved reliabile within the training range and capable of extracting information from limited signals. Classification and quantification should take place separately, outlining the development of concepts in which *neural networks arrays*, coupled for performance fusion to conventional procedures, classify a phenomenon first, to proceed subsequently to quantitative identification. Limited but promising results have also been obtained on experimental test cases. Such favourable aspects should not shadow the open problems encountered, in the first place the achievement of adequate *solution quality*, avoiding not only the known problem of convergence to local minima, but, far more substantial, providing reliable guidelines for strategies and topologies ensuring *generalisation and accuracy* on "unknown" signals. Specifically, future developments shall address training based on processed signals, treatment of multi d.o.f. systems and coupled mechanisms, together with a comprehensive laboratory and site tests program.

ACKNOWLEDGEMENTS

This work is part of the BRITE/EURAM NEWNET project, under grant with the Commission of the European Communities, whose financial support is gratefully acknowledged. The authors would also like to thank their partners: Professor J.R. Tomlinson, general coordinator, and Dr. K. Worden, Dept. of Engineering, University of Manchester, UK, Professor S. A. Billings and Dr. G.L. Zheng, Dept. of Automatic Control and Systems, University of Sheffield, UK.

REFERENCES

1. WASSERMAN P.D., Neural Computing, Theory and Practice. Van Nostrand Reinhold, New York, 1989.

2. LIPPMAN R.P., An Introduction to Computing with Neural Nets. IEEE Transactions on Acoustics, Speech and Signal Processing, 4-22, april, 1987.

3. HEBB D.O., The Organisation of Behaviour. John Wiley & Sons, New York,1949.
4. BILLINGS S.A., YAMALUDDIN R.D. & CHEN S., A Comparison of the Back-Propagation and Recursive Prediction Error Algorithms for training Neural Networks. Mechanical Systems & Signal Processing, 5, 233-255, 1991.
5. WERBOS P.J., Beyond Regression: New Tools for Prediction and Analysis in the Behavioural Sciences. Master Thesis, Harvard University, USA, 1974.
6. PARKER D.B., Learning Logic. Invention Report S81-64, File 1, Office of Technology Licensing, Stanford University, Stanford, California, USA, 1982.
7. RUMELHART D.E., HINTON G.E. & WILLIAMS R.J., Learning Internal Representations by Error Propagation. Parallel Distributed Processing, 1, 318-362, MA: MIT Press, Cambridge, USA, 1986.
8. BILLINGS S.A. & CHEN S., Extended Model Set, Global Data and Treshold Model Identification of Severely Nonlinear Systems. International Journal of Control, 50, 1897-1923, 1989.
9. PAO YOH-HAN, Adaptive Pattern Recognition and Neural Networks. Addison-Wesley, Reading, UK, 1989.
10. BROWN M. & HARRIS C.J., The B-Spline Neuro-Controller. Parallel Processing for Control, E. Rogers ed., Prentice-Hall, 1992.
11. BROOMHEAD D.S. & LOWE D., Multivariable Functional Interpolation and Adaptive Networks. Complex Systems, 2, 321-355, 1988.
12. CHEN S., BILLINGS S.A., COWAN C.F.N. & GRANT P.M., Practical Identification of NARMAX Models using Radial Basis Functions. International Journal of Control, 52, 1327-1350, 1990.
13. MINSKY M.L. & PAPERT S., Perceptrons. MA: MIT Press, Cambridge, USA, 1969.
14. CHU S.R., SHOURESKY R. & TENORIO M., Neural Networks for System Identification, IEEE Control and Systems Magazine, 10, 36-43, 1990.
15. CHEN S., BILLINGS S.A. & GRANT P.M., Nonlinear System Identification using Neural Networks. International Journal of Control, 51, 1191-1214, 1990.
16. NARENDRA K.S. & PARTHRASARAY K., Identification and Control of Dynamical Systems using Neural Networks. IEEE Neural Networks Trans., 1, 4-27, 1990.
17. MASRI S.F., CHASSIAKOS A.G. & CAUGHEY T.K., Structure-Unknown Nonlinear Dynamic Systems: Identification through Neural Networks. Smart Materials & Struct., 1, 45-56, 1992.
18. KUDVA J., MUNIR N., & TAN P.W., Damage Detection in Smart Structures using Neural Networks & FE Analysis. Smart Materials & Struct.,1,108-112, 1992.
19. GHABOUSSI J., GARRET J.H. & WU X., Knowledge-Based Modelling of Material Behavior with Neural Networks. J. Engng. Mech., 117, January 1991.
20. GARRET J.H. & GHABOUSSI J., Use of Neural Networks in Detection of Structural Damage. Computers & Structures, 42, 649-659, 1992.
21. BRITE/EURAM NEWNET Project on Neural Networks and new Signal Processing Procedures for Fault Detection in Civil Engineering Structures. 1rst joint Report to the Commission of the European Communities, Universities of Manchester (UK), Sheffield (UK) & "G. D'Annunzio" (Italy), October 1992.
22. WORDEN K. & TOMLINSON G.R., Modelling & Classification of Nonlinear Systems using Neural Networks. J. Mech. Systems & Signal Proc., to appear, 1993.
23. BILLINGS S.A. & TSANG K.M., Spectral Analysis for Nonlinear Systems. Part I & Part II, Mech. Systems & Signal Proc., 3 (4), 319-341, 1989.
24. BRANCALEONI f., SPINA D., VALENTE C., Damage Assessment from the Dynamic Response of Deteriorating Structures. Int. Workshop 'Safety Evaluation of Time-Variant and Nonlinear Structures Using Identification Approaches', Lambrecht, Germany, September 1992.

Expert System and Assessment of Earthquake Hazard Reduction
Système expert pour la protection des bâtiments contre les séismes
Expertensystem für den Schutz von Mauerwerksbauten gegen Erdbeben

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SUMMARY
This paper describes an expert system applicable to one and two storey buildings, representative of the background and methodology of experienced engineers familiar with the evaluation of existing unreinforced masonry buildings in accordance with the Los Angeles Building Code. Building properties have to be input. Code lateral forces are established and stresses in the main resisting elements including walls, piers, diaphragms, chords and various structural connections are determined. Actual stresses are compared with allowable ones. The expert system has been checked by application to three prototype buildings. Excellent correlation with traditional assessments was obtained.

RÉSUMÉ
Il est ici question d'un système expert applicable aux bâtiments à un et deux étages, capable de transmettre les connaissances et la méthodologie d'ingénieurs expérimentés, pour la vérification des constructions existantes en maçonnerie non armée, et en conformité avec le règlement de sécurité des constructions de Los Angeles. Après avoir entré les caractéristiques de l'ouvrage, ce système détermine les forces horizontales équivalentes à la norme et en déduit les contraintes dans les éléments porteurs principaux, tels que parois, piliers, diaphragmes, membrures et diverses liaisons structurales; les contraintes ainsi calculées sont ensuite comparées aux contraintes admissibles. Ce système expert a été testé en l'appliquant à trois prototypes de bâtiment et il a donné une excellente concordance avec les méthodes de contrôle traditionnelles.

ZUSAMMENFASSUNG
Der Beitrag beschreibt ein Expertensystem für ein- und zweigeschossige Gebäude, das das Hintergrundwissen und die Vorgehensweise erfahrener Ingenieure bei der Ueberprüfung bestehender Bauten aus unbewertem Mauerwerk wiedergibt. Nach Eingabe der Bauwerkseigenschaften werden die horizontalen Ersatzkräfte nach Norm ermittelt un daraus die Spannung in den Haupttragelementen - wie Wänden Preilern, Scheiben, Riegeln und verschiedenen tragenden Verbindungen - berechnet; diesen werden dann die zulässigen Spannungen gegenübergestellt. Bei der Validierung an drei Prorotypgebäuden ergab sich eine hervorragende Uebereinstimmung mit herkömmlichen Untersuchungsmethoden.

1. BACKGROUND

A large proportion of the particularly hazardous buildings in the world are constructed of unreinforced masonry. Many were erected prior to the implementation of building codes calling for specific earthquake resistance provisions. Demolishing and rebuilding the large stock of existing buildings is not generally a viable alternative, hence, much effort is being expended on the task of upgrading, or seismically retrofitting these structures.

Several guidelines have been developed to identify and evaluate the seismic risk of existing buildings but a significant factor in undertaking this task successfully is the experience of those engaged in it. Partially because of the irregular occurrences of damaging earthquakes, only a limited number of building officials can be expected to have had field experience of examining earthquake damage coupled with a thorough understanding of the principles and strategies of seismic retrofit work. This makes the assessment of earthquake hazard reduction a prime candidate for a knowledge-based expert system approach.

In 1981 the city of Los Angeles adopted an ordinance [1] to promote public safety and welfare by reducing the risk of death or injury that may result from the effects of earthquakes on unreinforced masonry buildings constructed before 1934. Past experience had shown that such structures are susceptible to partial or complete collapse during moderate to strong earthquakes. Division 88 of the Los Angeles building code provides systematic procedures and standards for identification and classification of unreinforced masonry bearing wall buildings based on their present use. Priorities, time periods, and standards are specified. The retrofit provisions of the Division are considered to be minimum standards for structural seismic resistance. Although they were established primarily to reduce the risk of life loss or injury, in severe seismic shaking compliance will not necessarily prevent loss of life, injury, or damage to upgraded buildings.

A contract awarded by the National Science Foundation to the Applied Technology Council with the objective of devising a methodology to determine potential earthquake hazards and identify the buildings or building components that present unacceptable risk to human lives resulted in the report [2] ATC 14, "Evaluating the Seismic Resistance of Existing Buildings." This document provides a practical guide to engineers for determining potential earthquake hazards in most types of existing buildings, including unreinforced masonry ones.

Such documents as the Los Angeles Division 88 and the ATC 14 represent agreement amongst groups of experts in the field of building rehabilitation about what the minimum acceptable standards for these buildings should be. The methodology presented can also provide an inspection "format" to be followed when actually inspecting the structures. This "format" ensures that all aspects of seismic rehabilitation established in the code are reviewed and analyzed.

The objective of the work reported in this paper was to develop an "expert system" computer program based on the methodology presented in both of these documents. The program complies essentially with the provisions of Division 88 of the Los Angeles buildings code and follows the basic procedures presented in the ATC report. The format ensures that all aspects of rehabilitation reflected in these documents, including present use, structural configuration and building condition, are reviewed and analyzed. The approach is based on the expert system shell EXSYS. Interface with Lotus 1-2-3 facilitates a spreadsheet approach to data handling. The expert system, containing 265 rules, was developed on a Hyundai Super 286 C IBM-compatible PC equipped with 312k of memory and 80,287 math coprocessor and can be run on any similar configuration.

2. THE EXPERT SYSTEM SHELL PROGRAM EXSYS

2.1 General Information

The commercially available EXSYS [3] shell program was chosen for the project reported. This shell does not contain any rules itself, but is designed to enable the user to create his own expert system by entering rules which will be processed and run by the EXSYS program. The user prompts the computer to help solve the problem by entering IF-THEN-ELSE rules explaining the steps involved in the decision-making process. The rules are a collection of English sentences and mathematical equations which can be easily read by anyone familiar with the problem domain. A rule is made up of a series of IF conditions and list of THEN and ELSE statements reflecting the probability of a particular choice being the appropriate solution to the problem. If the computer determines that all of the IF conditions in a rule are true, it adds the rule's THEN conditions to what it knows to be true. If any of the IF conditions are false, the ELSE conditions are added to what is known. The computer determines what additional information is needed and how best to get the information. If possible, the program will derive information from other rules rather than asking the user for information. This ability to derive information allows the program to combine many small pieces of knowledge to arrive at logical conclusions about complex problems. EXSYS derives information by backward chaining unless commanded to use the forms of forward chaining available in the program. It is written in the C language which is noted for its speed and compactness of code.

2.2 Hardware Used in the EXSYS Development

The computer used for development of the unreinforced masonry seismic hazard reduction expert system was a Hyundai Super-286C IBM compatible personal computer. A Rampage AT expanded memory board with 512k of memory and a 80287 math coprocessor was installed. Microsoft DOS version 3.2 was used.

3. THE EXPERT SYSTEM "URMDV88"

3.1 General Considerations

As unreinforced masonry buildings have been constructed in many different sizes and shapes, it is impractical to create a knowledge base that contains the necessary knowledge to analyze every possible building. Additionally, expert systems become less efficient as the problem they are programmed to solve becomes more broad. Consequently, the expert system reported, URMDV88, has been programmed to analyze buildings with only one or two stories with a square or rectangular floor plan. This specific scope makes it feasible to develop a knowledge base that can effectively analyze a building and meets the restrictions defined by the scope.

The expert system is named URMDV88 in recognition of the fact that the unreinforced masonry buildings are being analyzed in accordance with Division 88 of the Los Angeles Building Code [4], providing engineers with minimum guidelines for analyzing unreinforced masonry buildings to determine what, if any, actions are required of building owners to reduce the risk of death or injury that may result from the effects of earthquakes. These buildings are classified using parameters established in the code. Lateral load coefficients for the building or parts of the building are determined using the building's classification. Allowable loads and dimensions for structural members and components are defined in the code.

URMDV88 is programmed to determine these values specified in the code. The expert system requests information about the building and then derives the allowable values for the building. The system also calculates actual values and compares them to the derived allowable values. The report generator in EXSYS is then used to detail out the results of the analysis.

URMDV88 uses one choice in all of its rules. The choice is only used to ensure that a rule will fire if all of its conditions are verified. Rules will not fire unless the THEN portion of a rule has an established choice. All of the rules in URMDV88 were designed to output information to the report generator if they fire. Therefore, all of the rules must have the choice included in the THEN portion of the rule.

The allowable values are analyzed and defined by the expert system. The system is designed to calculate values for variables and compare these values to the code allowable values. Certainty factors are not used because the calculated loads or dimensions either meet code specifications or they do not. The use of one choice causes EXSYS to analyze the rules in the order that they are written in the knowledge base. Initial rules define the code parameters and the succeeding rules perform the comparisons. The report generator specification is designed to print calculated variable values or notes if a rule fires. The notes are statements of compliance or recommended actions. The variables or notes will be printed in the order that the rules fire. The report generator is used to develop a report that details the results of the calculations and also whether or not the code parameters have been met. The choice is not included in the report. The choice is given the same certainty or probability factor in all of the rules so that the rules will fire in a consistent order. The expert system uses all of the rules in the derivation of information.

3.2 Components of URMDV88

The expert system is contained in two knowledge bases. Blackboarding is used to transfer information from one knowledge base to the other. The first knowledge base is given the name URMDV88a and the second knowledge base is named URMDV88b.

URMDV88a classifies an unreinforced masonry building according to DIVISION 88 of the Los Angeles Building Code. The lateral load factors and allowable loads and dimensions for the building and its components are established in this section of the expert system. Allowable soil pressures are also established and then compared to actual foundation pressures.

LOTUS 1-2-3 is interfaced with URMDV88a in order to receive data pertaining to an existing building's material properties and dimensions of the various structural components. The spreadsheet INDAT.WK1 is used to do this. This spreadsheet is filled out before the expert system is run. The dimensions of the building's structural components are entered into INDAT.WK1. The spreadsheet calculates the weight of the building and its components. The dimensions and weights are saved to a file called VAR.PRN.

URMDV88a is instructed by the system's configuration file to read the data contained in the file VAR.PRN. The configuration file is named URMDV88a.CFG. This file also specifies the file names to be used when passing data between EXSYS and LOTUS. The file PASS.PRN is used to pass data from EXSYS to LOTUS 1-2-3. The file RETURN.PRN is used to pass data from LOTUS 1-2-3 to EXSYS. The configuration file is also used to instruct EXSYS to request the date and building name at the beginning of each run.

The knowledge for the first knowledge base is contained in the files URMDV88a.RUL and URMDV88a.TXT. These files are created by EDITXS when developing the expert system. This knowledge base contains 264 variables and 73 rules. When URMDV88a is run it automatically reads the VAR.PRN file. The system will then ask the user for the date and building name. The user then responds with the information that the system will request concerning the building's occupancy and structural components. This information is used to establish the various lateral load factors and allowable loads specified in the code. The system then calls 1-2-3 after this is accomplished.

The spreadsheet AUTO123.WKl is automatically loaded when 1-2-3 is called. This spreadsheet is used to instruct the user on which spreadsheet to call next. Different spreadsheets are required depending on whether the building is one story or two story. AUTO123.WK1 reads the number of stories from the file LWX.DAT which is generated by the INDAT.WK1 spreadsheet. The user is automatically given instructions on how to call the correct spreadsheet. This is done using the macro capabilities in 1-2-3.

The system will load the spreadsheet ONEST.WK1 if the building is a single story one. The spreadsheet will automatically import the files Vl.PRN, VP.PRN, and LWX.PRN from files created by the INDAT.WK1 spreadsheet. The spreadsheet also reads data generated by URMDV88a from the PASS.PRN file. The user will then fill out the highlighted cells in the spreadsheet. The spreadsheet calculates wall shears, diaphragm shears, and pier stresses using the appropriate factors generated by the expert system. The spreadsheet results are sent back to URMDV88a using the RETURN.PRN file.

The system will load the spreadsheet TWOST2.WK1 if the building is a two-story structure. This spreadsheet calculates building story shears and also the wall shears, diaphragm shears, and pier stresses in the top story of the building. In addition to the files listed above for the one-story building, this spreadsheet will automatically import the file V2.PRN from INDAT.WK1. Data is passed to the spreadsheet using the PASS.PRN file. The user fills out the highlighted variables and then follows the instructions that will call the spreadsheet TWOST1.WK1. The calculated shears and stresses are saved to files named TOL1N.PRN and TOL1T.PRN which will be imported by TWOST1.WK1.

TWOST1.WK1 calculates the wall shears, diaphragm shears, and pier stresses in the bottom story of the building. The user fills out the highlighted variables and the calculations are automatically made. The results of both TWOST2.WK1 and TWOST1.WK1 are automatically saved to the RETURN.PRN file which is read by URMDV88a.

The system will return to URMDV88a when the user completes the work in the spreadsheets and quits the 1-2-3 program. URMDV88a will begin at the same point it left when the 1-2-3 program was called. The expert system will then question the user on soil conditions observed at the building site. The report generator file is used to create a file which stores the results of the information derived and calculated in URMDV88a. This data file is named INPUT.DAT. The information included in this file includes the information read from the spreadsheets and URMDV88a.

The second knowledge base is called URMDV88b and is contained in the files URMDV88b.RUL and URMDV88b.TXT. This knowledge base contains 265 rules and 338 variables and compares the actual loads, stresses, and dimensions of various structural components of the building to the allowable values. The URMDV88b.CFG file instructs the system to automatically read the INPUT.DAT file generated by the first knowledge base. There is no user interaction or external programs called in this knowledge base. The results are printed to a file specified by the report generator.

3.3 Directories and Path Names

Path names tell the computer where to find the files and programs required by the expert system. The EXSYS program gives the programmer the option of using different directories to store programs and files.

URMDV88 was developed with both EXSYS and the LOTUS 12-3 program in the same directory. The directory name is EXSYS and it is on the C drive of the computer. All the files used by URMDV88 and the 1-2-3 spreadsheets are also stored in the EXSYS directory.

4. ASPECTS OF URMDV88 EXPERT SYSTEM

4.1 General

Space limitations prevent all the considerations taken into account in the Expert System being described in detail. A representative selection is presented below.

4.2 Building Geometry and Weight

The spreadsheet INDAT.WK1 is used to input the dimensions of the walls, parapets, roof diaphragm, floor diaphragm, and foundation. The roof dead weight, floor dead weight, weight of masonry, and contingency weights are also input into the spreadsheet. The contingency weights are to allow for additional weights that may be applied on the horizontal diaphragms such as partition loads.

The spreadsheet automatically calculates the weight of the building and its components. This calculation is performed by multiplying the weight of the masonry times the volume of each of the building components. The weight of the components are then summed up to determine the total building weight. The weight of the footing is not included in the building weight. The weight of the footing is calculated in the spreadsheet by multiplying the volume of the concrete in the masonry wall footings by 150 lbs. per cubic foot.

URMDV88a approximates the soil bearing pressure created by the lateral loads generated in earthquakes using the flexure formula. The system calculates the moment created by the lateral loads by multiplying the lateral load by the distance from the lateral load to the ground elevation. This moment is calculated in both principal directions of the building.

The second moment of area of the foundation is calculated in both principal directions of the building by the spreadsheet. The second moment of area of the foundation components are summed to calculate the total foundation second moment of area in each direction. Slabs on grade are not included in the footing weight or moment of inertia calculations.

4.3 Building Classification

Section 91.8803 of the Los Angeles Building Code contains the definitions of the types of unreinforced masonry buildings used to determine the building classification. The building type depends primarily upon the occupant load of the building. The procedure for determining the occupant load is specified in Section 91.3301(d) of the Code. The rating classifications are established in Table No. 88-A as described in Section 91.8804 of the code.

The classification of the building is performed in URMDV88a. The user is required to supply the correct values for Qualifiers 1 through 5 as required by the expert system. Rules 1 through 7 contain the knowledge required to classify the structure. The expert system derives the building classification based on these rules.

4.4 Horizontal Force Factor

Section 91.8808(a) of the code specifies the procedure required to establish the minimum total lateral force that acts on the building. The following equation is used to define the force:

$$V = (IKCS)W \tag{1}$$

The weight of the building is represented by the letter W and the horizontal force factor for the building is denoted by the (IKCS) term. The value of (IKCS) need not exceed the values set forth in Table No. 88-D of the code. The horizontal force factors are based on the buildings classification and will be determined by the expert system without user input. Rules 8 through 10 determine the horizontal force factor for the building.

Section 91.8808(b) of the code specifies the minimum lateral force that acts on an element of a building. This force is represented by the following equation:

$$F_p = (IC_pS)W_p \tag{2}$$

The weight of building element is represented by the W_p term. The (IC_pS) term is determined by two tables in the code. Table No. 88-E provides the maximum required value for the product of I and S based on the building classification. The maximum values for C_p are provided in Table No. 88-F.

The expert system determines the value of IS in Rules 8 through 10. The total horizontal force factor for any element of the building is determined by the expert system in Rules 11 through 28. The user is required to supply the values to Qualifiers 7 and 9 to identify the building elements contained in Table No. 88-F which are observed during the building inspection.

4.5 Allowable Shear Stress for Tested Unreinforced Masonry Walls

Section 91.8809(g)1 of the code specifies the procedure used to determine the design seismic in-plane shear stress that is allowed for the unreinforced masonry walls in the building. The design shear stress is substantiated by tests performed as specified in Sections 91.8809(e)3 and 4. The design stress is related to the test results in accordance with Table No. 88-J of the code. Interpolation is allowed in this table.

There are two types of test allowed by the code. The test specified in Section 91.8809(e)3 is the in-place shear test. The test specified in Section 91.8809(e)4 is the core test. These tests have to be performed by testing agencies approved by the building department. The user is required to supply the expert system with the value for Qualifier 10 which identifies the test method used. The system will then request the value for applicable test results from the user. This is either Variable 12 or Variable 14 depending on which test is performed. The value should not include the addition of 10 percent of the axial stress allowed due to the weight of the wall. This increase is included in the spreadsheet portion of the system if it is required.

Rules 29 through 31 determine the design shear stress if the seismic in-place shear test is utilized. Rules 32 through 36 determine the design shear stress if the core test is selected. These sets of rules perform the interpolation allowed by the code.

4.6 Allowable Height: Thickness Ratio of URM Walls

Section 91.8809(b)1 of the code specifies that unreinforced masonry walls analyzed in accordance with Division 88 may provide vertical support for roof or floor construction and also resistance to lateral loads. The bonding of such walls is required to comply with section 91.2412(b)1 of the code.

Section 91.8809(b)1 goes on to specify that tension stresses due to seismic forces normal to the wall may be neglected if the wall does not exceed the height- or length-to-thickness ratios and in-plane shear stresses as set forth in Table No. 88-G of the code. Buildings with crosswalls, as defined by Section 91.8803, have different allowable ratios than buildings without crosswalls. The allowable ratios in the table can only be used if the wall contains the minimum mortar quality required by Section 91.8809(e) and the building has a rating classification II, III, or IV. All walls in Class I buildings are required to be analyzed in accordance with Section 91.8808(f) of the code.

Rules 38 through 41 assign the allowable ratios for one- or two-story buildings that Table No. 88-G can be applied to. Rule 37 is used to instruct the user to analyze the walls for stability in accordance with Section 91.8808(f) if the minimum mortar quality standards are not met. Rule 42 instructs the user to use Section 91.8808(f) if the building is a Class I structure.

4.7 Allowable Shear Values for Horizontal Diaphragms

Section 91.8809(b)2 of the code specifies that existing materials may be used as part of the lateral load-resisting system provided that the stresses in the materials do not exceed the values shown in Table No. 88-H. This identifies various types of horizontal diaphragms and their allowable shear values. The user provides the values for Qualifier 14 to identify the roof diaphragm and Qualifier 15 to identify the floor diaphragm for two story buildings. The expert system then assigns the allowable shear values using Rules 43 through 45 for the roof. Rules 47 through 50 assign the values for the floor diaphragm if the building has two stories.

4.8 Horizontal Diaphragm Supported by URM Walls

Section 91.8810(b)3 of the code specifies that ledges or columns shall be installed to support vertical loads of the roof or floor members where trusses and beams, other than rafters or joists, are supported on masonry. The user is required to supply the values for Qualifiers 18 and 19 which identify the roof and floor support systems, respectively. Rule 46 sends a note to the project report if ledges or columns are required to support the vertical roof loads. Rule 51 sends a note to the project report if ledges or columns are required to support vertical floor loads for two story buildings.

4.9 Interface with LOTUS 1-2-3

Rule 52 calls the 1-2-3 program and loads the AUTO123.WK1 spreadsheet. Qualifier 11 contains the RUN command. The values of variables derived by the expert system that are required to calculate and analyze the in-plane stresses for unreinforced masonry walls is sent to the spreadsheets in the PASS.PRN file.

4.10 In-Plane Stresses for One-Story Building

The spreadsheet ONEST.WK1 is called by URMDV88a to calculate the base shear for the building, wall shears, diaphragm shears, and stresses in wall piers due to in-plane seismic loading. The spreadsheet automatically imports the required data to calculate the base shear, wall shears, and diaphragm shears. The user is required to input the pier dimensions, pier end conditions, and weight the piers are supporting before the pier stresses are calculated.

The base shear is calculated using the formula (1) discussed in section 4.4 above. The base shear is calculated in both principal directions of the building. The total weight of a building that contributes to the seismic loading along one principal axis is usually different from the weight that contributes to the loading along the other principal axis. The lateral load is assumed to be resisted by the shear walls that are parallel to the direction of loading. These walls feel the weight from the parapets, roof diaphragm, one half of the walls that run perpendicular to the load, and themselves. The force in the walls that run perpendicular to the direction of the load is resisted at the diaphragm level and at the ground level. The diaphragm transmits the shear generated by the weight of the upper half of the perpendicular walls to the walls parallel to the load. The same horizontal force factor is used in both directions.

The spreadsheet assumes a flexible diaphragm and the base shear is distributed to the walls by the tributary area supported by each wall. The diaphragm shear at each wall is also calculated. This calculation is made by dividing the wall shear by the total length of the wall. This assumes that the wall has a continuous chord which connects all the piers.

The seismic wall shears are distributed to the piers by the relative rigidities of the piers. The calculations performed in the spreadsheet assume that the piers are parallel to each other. The user can select either a fixed end condition or cantilever end condition for each pier. The cantilevered condition is the default condition. The shear stress in a pier is calculated by dividing the shear carried in the pier by the cross sectional area of the pier.

Section 91.8809(g)2 of the code specifies that compressive stresses in unreinforced masonry walls that have a minimum design shear value of 3 psi shall not exceed 100 psi and that design tension stresses for these walls are not allowed.

The spreadsheet calculates the axial stress in each pier by dividing the weight supported by each pier by its cross sectional area. Automatic calculation of the supported weight is undertaken by assuming that the pier supports that portion of the wall and the parapets proportional to the length of the pier.

The spreadsheet calculates the bending stress in each pier created by the seismic shear using the flexure formula. The moment created in each pier is calculated by multiplying the pier shear by the height of the pier for piers that have a depth that is at least 80 percent of the length of the wall. The moment arm is taken as one half the height of the pier for piers whose depth is less than 80 percent the length of the wall. The bending stress is calculated by dividing the moment in the pier by the section modulus of the cross section of the pier. Tensile stresses are denoted as positive stresses.

The spreadsheet calculates the maximum compressive stress in each pier by summing the axial stress and the bending compressive stress. The maximum tensile stress is calculated by summing the axial stress and the bending tensile stress.

The code states that the allowable shear stress in unreinforced masonry walls may be increased by the addition of 10 percent of the axial stress due to the weight of the wall directly above the pier in consideration. The spreadsheet allows the user to take this increase if the actual calculated pier stress is greater than the allowable shear stress taken from Table No. 88-J. This is done by entering the dimension from the top of the parapet to the pier. The spreadsheet will then automatically calculate the allowable stress increase that can be taken for the pier and add it to the allowable stress.

The spreadsheet compares the actual shear stresses in each pier with the allowable stresses. The message "OK" will be displayed if the pier is not overstressed. The message "IN-PLANE SHEAR EXCEEDED" will be displayed if the calculated shear stress exceeds the allowable shear stress. The spreadsheet will send a flag to the expert system that indicates whether or not the allowable shear stress is exceeded in any pier for each wall. The spreadsheet sends the maximum compressive stress and tensile stress for each wall to the expert system for comparison to the allowable stress values.

4.11 Other Considerations

Further portions of the expert system cover such aspects as the in-plane stresses for two-story buildings, soil bearing pressures, parapet stabilization, wall tension anchors, diaphragm shear comparison, diaphragm shear bolt spacing, wall stability analysis for out-of-plane seismic loading, chord force analysis, analysis of in-plane shear stress, and analysis of tensile and compressive stress generated by in-plane loading. These additional aspects call upon more than 200 separate rules to achieve the appropriate analyses.

5. VERIFICATION OF THE EXPERT SYSTEM

5.1 The Test Cases

Validation of the expert system was undertaken by applying it to the analysis of three buildings in the Los Angeles area which had been subjected to seismic retrofit. Two of the buildings are of one-story, the third has two stories. The first building is a Class I structure whereas both the others are Class III.

The first building has two shear walls resisting the lateral loads in each of the two principal footprint axes. The second building has three shear walls in one direction and two in the orthogonal axis. The third has two shear walls on each principal axis and both a floor and a roof diaphragm.

Aspects investigated included parapet stabilization, wall tension anchor provision, diaphragm shear bolt provision, wall stability, chord forces, in-plane shear, and tensile and compressive stresses.

Excellent agreement was obtained between the actual deficiencies identified and remedial measures prescribed by the engineer and those derived using the expert system in all but three instances.

In the first of these, the expert system concluded that one wall was stable in the second test-case building, whereas the engineer judged it to be unstable. The explanation for the discrepancy is that whereas the expert system used the average height of the wall, the engineer was aware that the height varied and the taller section was less stable. The expert system user could avoid the mismatch by feeding in the maximum height of the wall as the average height, however, this would tend to give rise to an over-conservative retrofit solution. Since the report generated by the expert system lists the maximum allowable height for each wall, it is convenient to review the system's recommendations and to fine-tune as necessary.

The second and third areas of disagreement involved the in-plane shear and tensile stresses for one pier in the third test case. The expert system prescribed reinforcement for both load cases at this pier, whereas the engineer chose to use his judgement to determine that the building's new roof diaphragm would be lighter than the original one, resulting in smaller values of pier stresses. The allowable stresses were within two percent of the actual shear calculated using the heavier roof which the engineer judged to be acceptable, whereas the expert system does not have the ability to exercise such discretion.

6. CONCLUSION

On the basis of the limited testing undertaken, the expert system is judged to be functioning as intended and provides the basis of a satisfactory solution to the objective undertaken.

7. ACKNOWLEDGEMENT

The work described was undertaken by the second author as partial satisfaction of the requirements for his M.S. degree [5], under the supervision of the first author. The very significant contributions of Dr. Eugene Gershunov, President of Earthquake Engineering, Inc., Irvine, California are recorded with gratitude.

8. REFERENCES

1. Los Angeles Municipal Code, "Earthquake Hazard Reduction in Existing Buildings", Ordinance No. 154,907: 1981.

2. Applied Technology Council, "Evaluating the Seismic Resistance of Existing Buildings", ATC 14, 1987.

3. Expert System Development Package, EXSYS Inc., Albuquerque, New Mexico, 1985.

4. City of Los Angeles, Building Code, 1985 edition.

5. Haynes, Tod E., "An Expert System Approach to the Assessment of Earthquake Hazard Reduction in Unreinforced Masonry Buildings", M.S. thesis, University of California, Irvine, 1990.

Expert System for Integrated Cable Inspection

Système expert pour le contrôle intégral des câbles

Integrale Kabelprüfung mittels eines Eypertensystems

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SUMMARY

The premature replacement of cables of different bridges made it clear, that inspections must include bridge cables. A kowledge-based expert system for the inspection and the evaluation of different cable structures is based on a thorough theoretical knowledge of all members of the structure, a feed-back of field tests, an application of different technologies and of numerous results of inspections. For final evaluations the geometric form of the cable , the cable alignment, the construction of end sections and end-terminations as well as the conditions of clamp-seatings must be discussed. Based on this information the structural safety and further use can be evaluated. Recommendations for suitable maintenance and rehabilitation measures can be given.

RÉSUMÉ

Un système expert a été développé afin de permettre des inspections périodiques pour la maintenance et la sécurité des câbles de ponts haubanés. Défini comme système d'inspection intégrale, il comporte la connaissance théorique approfondie de tous les éléments porteurs, les résultats d'essais sur le site, l'utilisation de diverses méthodes d'essais non destructifs et d'innombrables résultats d'inspections. L'appréciation finale tient compte de la forme géométrique du câble considéré, de son allure, de la conception de ses ancrages et de l'état de ses sabots de serrage. A partir de cet ensemble d'informations, il est possible de déterminer la sécurité structurale et la durée de vie restante, ainsi que de fournir des recommandations relatives à des mesures appropriées d'entretien et de réhabilitation.

ZUSAMMENFASSUNG

Für den Unterhalt und die Sicherheit von Ingenieurbauwerken sind periodische Inspektionen nötig, insbesondere bei Brückenkabeln. Zu diesem Zweck wurde für unterschiedliche abgespannte Tragwerke ein Expertensystem entwickelt. Als integrales Inspektionssystem umfasst es gründliche theoretische Kenntnisse aller Tragelemente, Ergebnisse von Feldversuchen, die Anwendung verschiedener zerstörungsfreier Testverfahren und zahlreiche Inspektionsergebnisse. In die endgültige Beurteilung sind die geometrische Form des betreffenden Kabels, sein Verlauf, die Gestaltung der Verankerungen und der Zustand der Klemmenschuhe einzubeziehen. Aufgrund dieser Informationen können die Tragsicherheit und weitere Lebensdauer ermittelt sowie Empfehlungen für geeignete Unterhalts- und Sanierungsmassnahmen agegeben werden.

INTRODUCTION

To evaluate the maintenance and safety of engineered structures periodic inspections are mandated. The premature corrosion of cables of different bridges - which forced their early replacement - made it clear that these inspections must include bridge cables. The inspection of bridge cables today is based on a mature technology, which has been widely used over the past twenty years. In Germany the ICI (Integral Cable Inspection) is practised, developed by DMT-Rope-Testing-Institute. This Integral Cable Inspection is built on a thorough theoretical knowledge of the condition and properties of the materials in question (wire, cable, socket), of the structural design as well as of the behaviour of the component parts when subjected to static and dynamic stress. Further on this Integral Cable Inspection consists of a feed-back of sixty years of field tests, practical application and results of cable inspections by

- extended visual inspections
- adapted NDT technologies such as
  - electromagnetic methods
  - ultrasonic testings
  - electrooptic inspections

The primary task of ICI is to prepare a report which includes a reliable assessment of the external and internal condition of the cables. Based on this information, their structural safety and further use can be evaluated. In addition, the owner can be furnished with recommendations for suitable maintenance and rehabilitation measures. The following are significant damage-related ICI findings:

- Damage to the corrosion protection,
- Evidence of external and internal corrosion,
- Mechanical distortions and damage,
- Broken or cracked wires,
- Adverse installation and environmental conditions, and
- Material damage caused by fatigue or external events.

Frequently these findings are caused by structural or constructional details. Also, environmental conditions can be significant. The following describes parts of Integral Cable Inspection methods which have been used for these examinations, including some noteworthy findings and conclusions.

TYPES AND CONSTRUCTIONS OF BRIDGE CABLES

Cables of suspension or cable-stayed bridges and guys of broadcast towers, chimneys, hall roofs or similar structures are high-strength tension members of the load-carrying system. Tension forces are applied via suitable end fittings, such als poured spelter sockets, resin sockets or clamps.

Cables for these structures are mainly of the fully-locked type. Spiral strands or stranded cables, as well as parallel wire strands or cable bundles, are also used. Fully-locked cables and spiral strands usually have diameters up to 110 mm. The largest fully-locked cables, manufactured for a bridge in Bangkok, have a diameter of about 180 mm. Larger cables are possible, but construction, handling and transportation problems have precluded their use. The need for larger cross-sectional areas is met by cable bundles. Although they are easy to manufacture, this alternative is problematic. It is very difficult or even impossible to inspect, maintain, repair or replace parts of a cable bundle. The distinct features of parallel wire bundles and cables must be recognized for their inspection and evaluation. The strength of cables is always less than the aggregate strength of their individual wires. Bundles of parallel wires are not subject to such a strength reduction. On the other hand, a broken wire in a wire bundle reduces the strength over its entire length, while a broken wire in a cable regains its full strength after a few lay lengths because of friction. The following discussion does not require a distinction between cables, cable bundles and parallel wire bundles. The generic term cable will be used.

INTEGRAL INSPECTION METHODS FOR CABLE SUPPORTED STRUCTURES (ICI)

The inspection of long-span suspension cables or high-rising guys poses numerous problems. But it is inevitable to inspect these cables from end-connection to end-connection. The dimensions and arrangement of these cables alone cause difficulties for the inspector. Any cross-section along the load-carrying length of these cables can be the weakest. Therefore, a reliable inspection requires unrestricted access to the cable under test over its entire length. These cables, between terminations, may be several hundred meters long. Occasionally, existing technology will not allow an inspection of certain cable sections. Then, cables can only be evaluated by logical inference with all its imponderabilities.

Theoretic Knowledge About Material and Cable Specifications

As a basis for later examinations and evaluations, all significant material specifications and cable properties must be ascertained by quality control procedures and acceptance tests. These evaluations include tensile tests and, possibly, fatigue loading tests of sections of the original cable.

Extended Visual Inspections

Based on a thorough theoretical knowledge an extended visual examination is the most important component of all inspections, Figure 1. The primary objective of a visual examination is to determine the external condition of the cable and to find exterior damage of the corrosion protection. Furthermore, visible changes of this surface frequently indicate internal damage. For the visual inspection of guyed structures of moderate height, a climbing or telescope crane is often adequate. The bridge cable inspection device developed for and owned by the government of Germany allows a safe visual inspection of most large bridges in Germany. All NDT-technologies are good helps to ensure

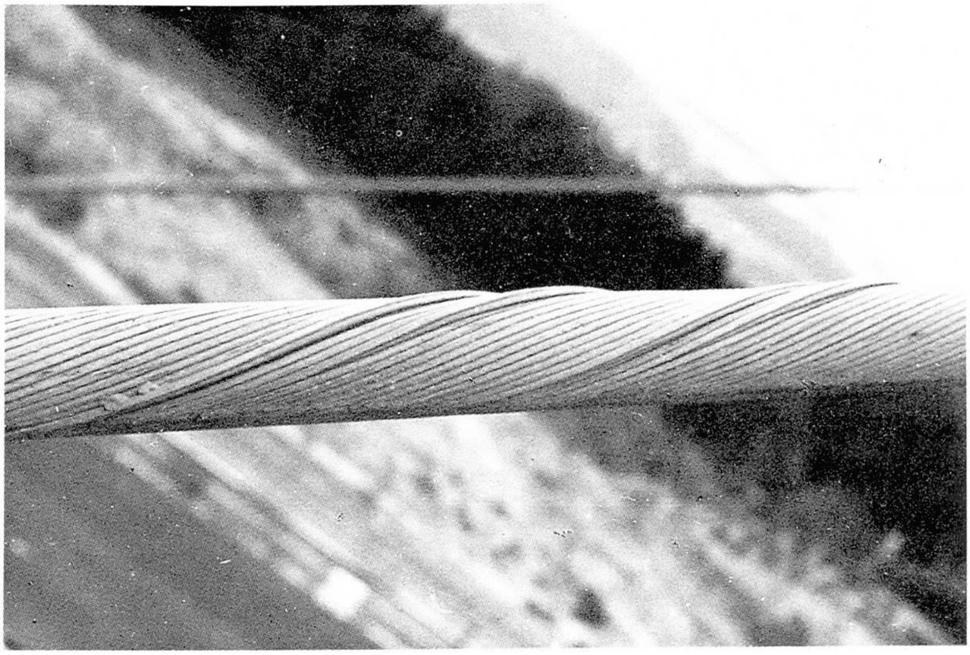

Fig.1: Mechanical distortion

the result of a visual examination but it must be pronounced that all the following NDT-technologies remain restrictive helps without a visual inspection.

Electromagnetic Inspection

Electromagnetic (EM) inspections allow examinations of a cable's interior. These inspections show external as well as internal cracked or broken wires, abrasion and corrosion. Practical instruments for in-service wire rope inspection, were first developed by DMT-Rope-Testing-Institute and University of Stuttgart in 1930. Since then, these procedures have been improved and adapted for novel applications by using advanced technologies as they became available. Instruments - which can simultaneously detect localized faults and measure loss of metallic cross-sectional area were used for the inspection of bridge cables and guys in Germany since about 1970. All present EM instruments are usually hinged.

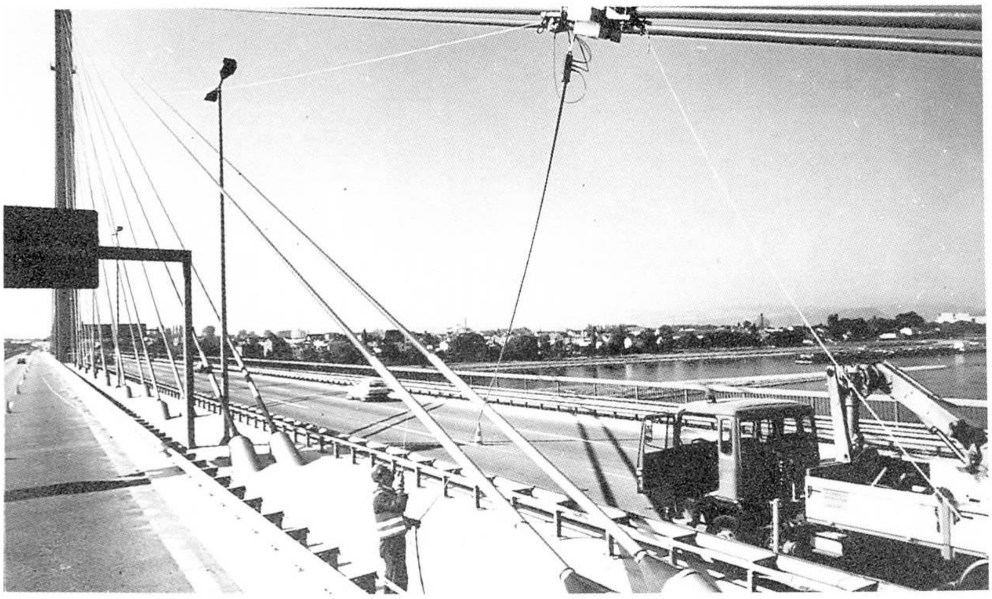

Fig. 2: Working situation

To perform an inspection, the instruments are pulled along the cable with a winch, Figure. 2. While the instruments travel along the cable test signals are recorded. These signals can be recorded or stored and processed by a portable data acquisition computer. The EM-inspection is easy to be performed. But the interpretation of the graphs is hard. Inspectors who dont regulary interpret EM graphs will fail.

Inspection of End Sections of Cables by Electro-optic Methods

The end sections of cables are frequently situated in narrow spaces where only an endoscope or borescope allows sufficient vision for a photographic or video documentation. The reason of nearly 60 % of all problems with cables lies in the structural design of this region.

Ultrasonic Testing

Terminations and end sections of cables constitute stress concentration points and are therefore particularly susceptible to damage. In addition, access to these segments is often more than difficult. Therefore, the inspection of these areas requires additional efforts and, under certain conditions, specialized inspection techniques and equipment. For example, specially adapted ultrasonic inspection methods, developed by DMT-Rope-Testing-Institute, can detect flaws and corrosion, even inside the end sockets. Wire breaks and cracks up to 600 mm inside the spelter or resin socketing can be reliably detected, Figure 3.

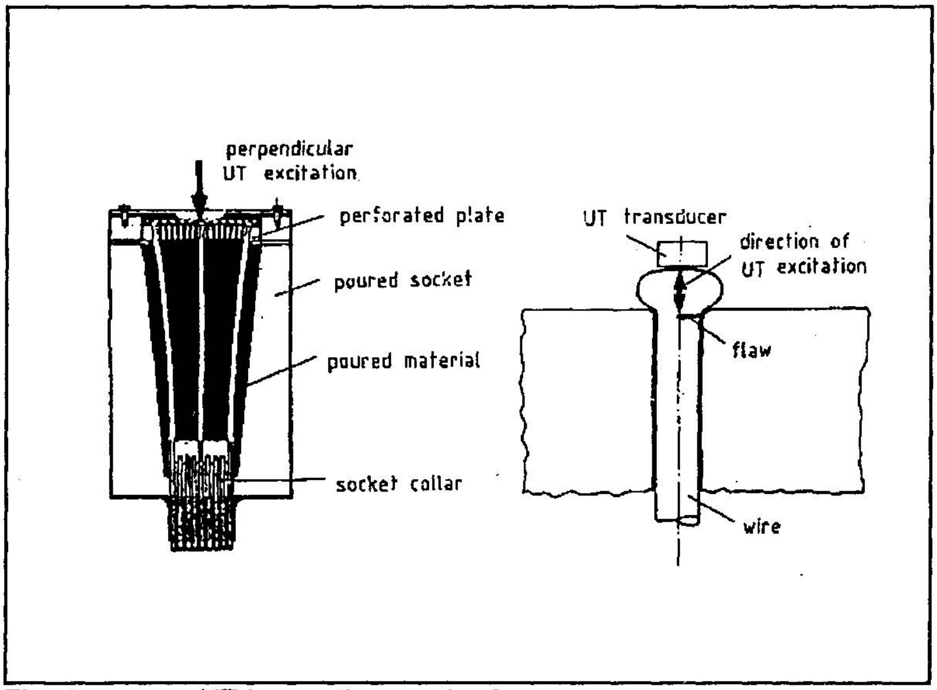

Fig. 3: UT inspection method

RESULTS OF ICI'S PRACTICAL APPLICATION

The following sections describe some findings of previous examinations.

Cable alignment

An alignment which allows unobstructed access between cable terminations is important. An unsuitable cable arrangement can make the complete inspection of the cable, rehabilitation of the corrosion protection, or other work difficult or impossible. Under adverse conditions, maintenance can only be performed to a limited extent and with difficulty. Often, inspections are possible only by using an endoscope. In some installations, cables contact adjacent cables or other structural members. In other cases, cables are led through openings of steel or concrete members which are too small. In these cases, wind can make cables rub against structural members. Under relatively favorable circumstances, this rubbing action will cause damage only to the corrosion protection. However, rubbing can also cause fretting corrosion or other damage, like cracking, of the wire surfaces. Under ideal conditions, the design of a structure should not require the cable to be deflected over its entire load carrying length.

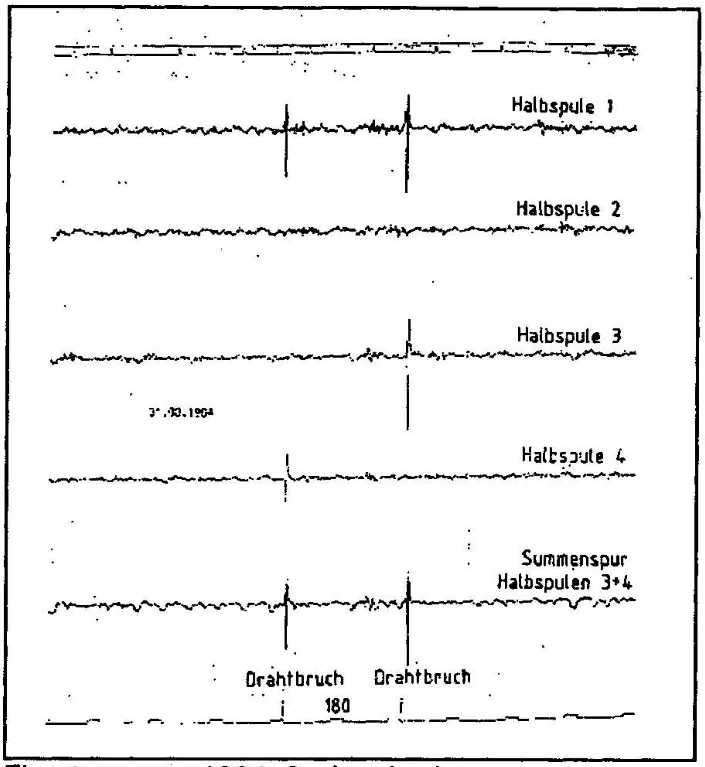

Fig. 4: 1984, 2 wires broken

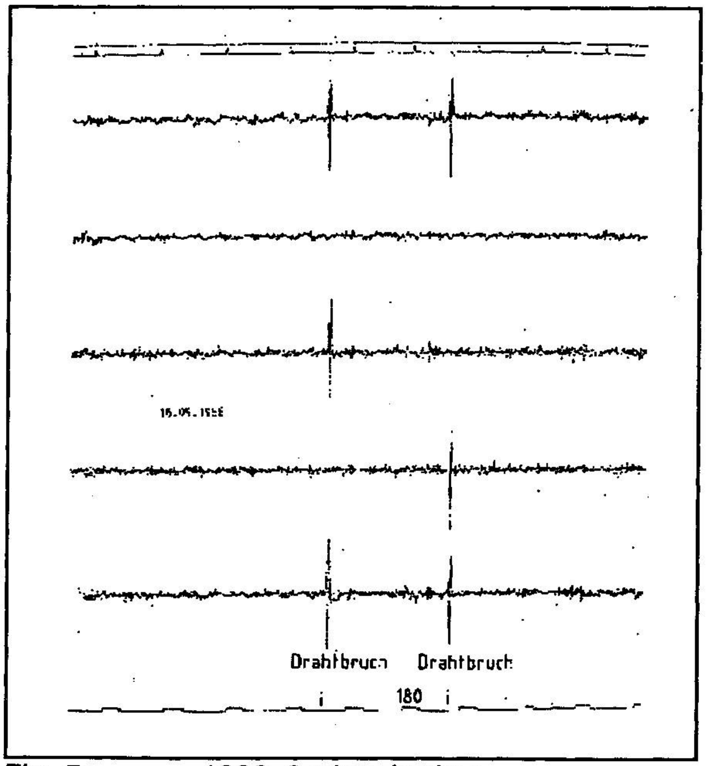

Fig. 5: 1986, 2 wires broken

EM-Inspection

Some bridge cables have been inspected repeatedly because of suspicious graphs. Figure 4 shows the graph gained in August 84 with two wires broken. Two years later, in Sept. 86, the graph for the same cable section is shown in Figure 5. By reason of the dynamic stress the spaces between the ends of wire breaks have increased and consequently the magnetic field measured has also changed. A third test on the same cable section was carried out on May 90. In addition to the two already ascertained wire breaks, a third incipient wire break in the same section of the cable is indicated in the graph (Figure 6). To detect corrosion under an undamaged corrosions protection coating is as important as to detect wire breaks! Figure 7 and Figure 8.

End terminations

Poured cable connections are more complex than cable attachments which use clamps. For poured connections, attention must be given f.e. to left-over serving bands at the base of the socket, to cracks, to cavities in the poured material, and to material which, because by thermal setting, has crumbled away. For clamped connections, firm seating of clamps and wedges must be verified. Furthermore, changes in the cable surface near and in contact with the clamps frequently indicate problems. For older structures, anchorage arrangements are often susceptible to damage. Moreover, these end connections are often anchored in the ground or embedded in concrete foundations and are accessible only under unusual conditions and with difficulty. In other cases, constructional details at the base anchorage allow the accumulation of water and debris, Figure 9.

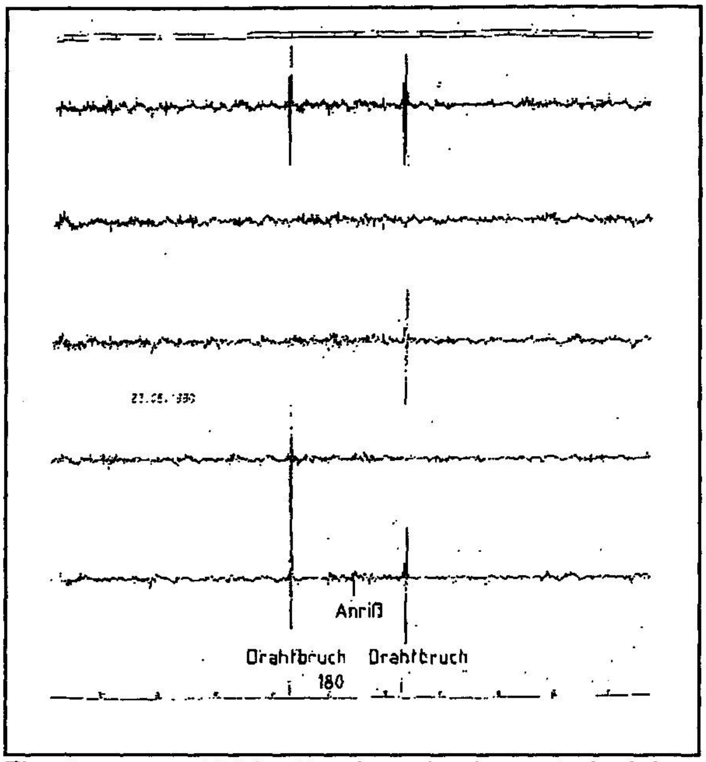

Fig. 6: 1990, 2 wires broken, 1 incipient crack

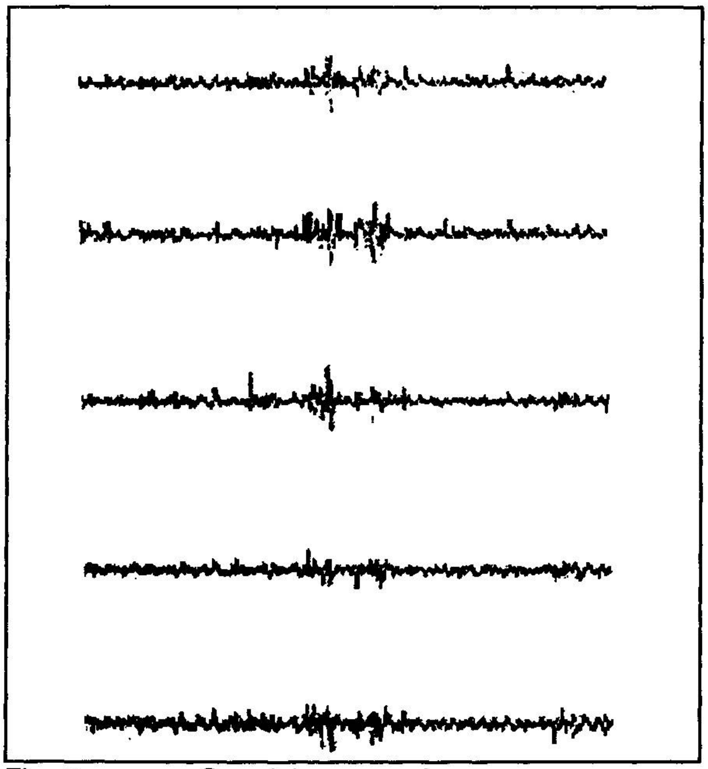

Fig. 7: Suspicious graph

Band and clamp seatings, saddle bearings, splayed anchorages

At points of directional change and in locations where forces are applied, the cable is subject to additional stresses. In particular, potential stress points are located along the restraining edges of end fittings. This can cause damage to the outside wires. For example, at clamping locations in suspensions bridges, the cable is forced into the shape of a polygon. Realistically, after opening and removing a clamp, the preexisting condition cannot be restored. Higher stresses on the cable and its wires are to be expected. This fact requires a careful evaluation whether or not a more accurate examination with opened clamp and band seatings is justified. Similarly, the individual wires of a cable which is deflected at saddles or splay anchorages are subject to additional stresses. At these locations, water accumulation - for example at gaps in clamps - combined with a possible reduct-ion of the coating can cause accelerated corrosion. Furthermore, rubbing at loose clamps - possibly aggravated by corrosion - can cause broken wires. Early detection of these wire breaks is hard because a visual inspection at these locations is usually difficult or impossible. Therefore, the inspector must rely on secondary indicators, such as color changes on the surface, shifts and cracks in the corrosion protection coat-ing, acoustic indication of movement, etc. Knowledge of structural details of a saddle or a splay anchorage is vital for an in-depth assessment. The base anchorages in older but also in some new - cable structures are especially susceptible to adverse environmental conditions. Penetration of water laden with deicing salts can cause severe corrosion of the end terminals. Salt water is particularly destructive when nonferrous metals are used as soft inserts at sockets or as padding for saddle supports and clamps.

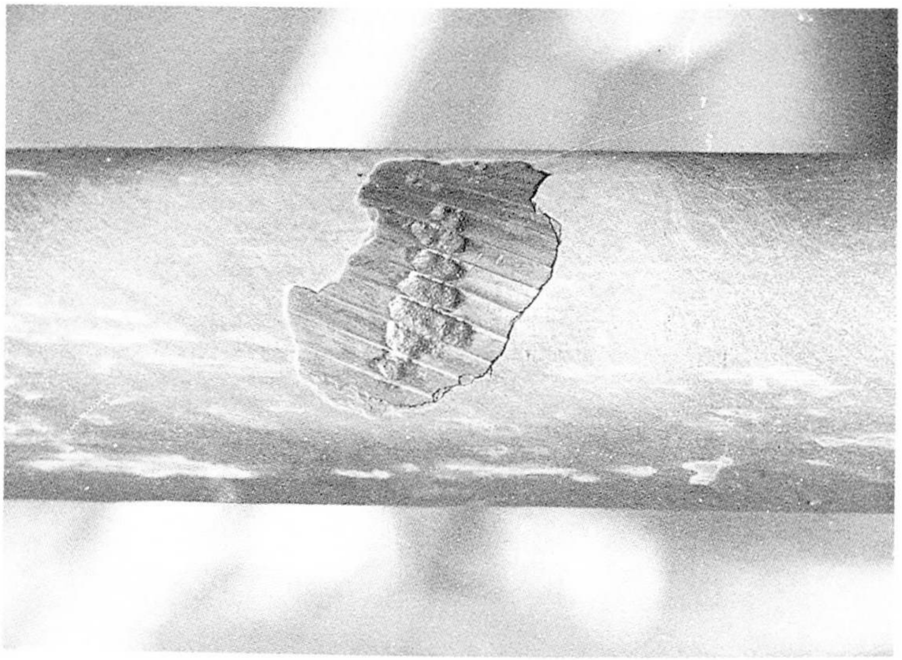

Fig. 8: Corrosion under coating

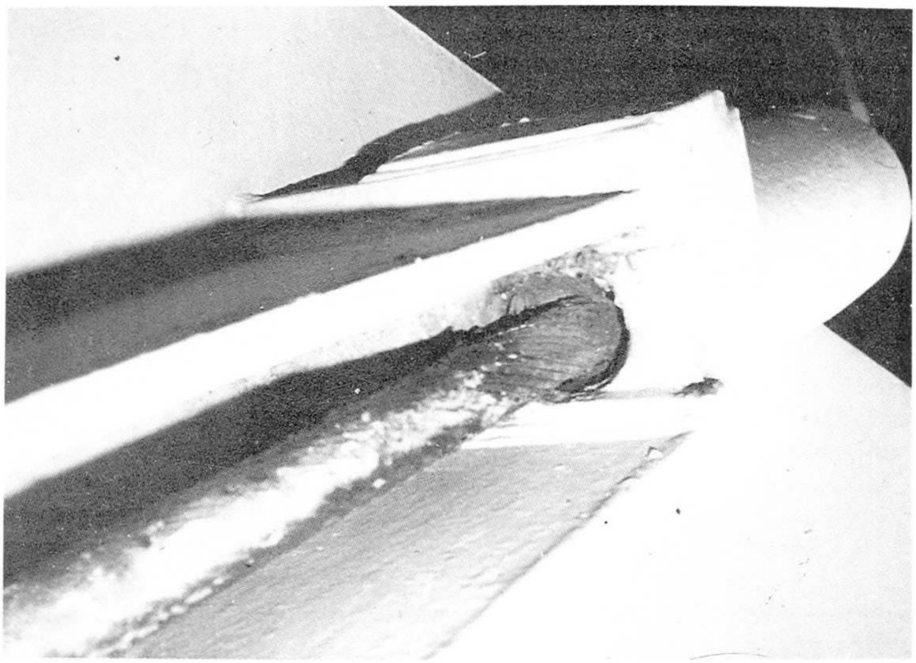

Fig. 9: Badly designed anchorage

Designs of corrosion protection

The design and consumption of corrosion protection of a cable plays an important role on the cable's life. Nearly about 50 % of a cable's troubles are caused by an unsufficiant corrosion protection. In the past, it was common practice to embed steel members of structures, including cables, in concrete or grout. This procedure makes an inspection difficult. However, this was not considered a serious problem. Load carrying cables were believed to be not susceptible to fatigue damage. Furthermore, grouting was considered a permanent corrosion protection. This practice has caused numerous problems. Therefore, it is hard to understand why load carrying members, such as cables and wire bundles, are still being constructed not inspectable. Although the use of protective plastics is promising and new, the previous basic problem remains: The load carrying elements cannot be visually inspected, which makes an assessment of their condition possible only by electromagnetic inspection. Even under normal conditions, varying external temperatures can cause water to penetrate a plastic coating through hair fissures and other crevices. Then, under an apparently undamaged surface, corrosion can develop undetected. Initial contamination of the cable by chemicals, sand, etc. can accelerate the corrosion process.

Fig. 10: Corrosion under a clamp seating

SUMMARY AND CONCLUSIONS

Longtime experience amply justifies regular periodic Integral Cable Inspections of bridge cables. However, there are no uniform and prescribed rules for these inspections, but one: a cable must be inspected from one end-connection to the other. Procedures for each structure must be individually designed and carrried out. For an extended visual inspection of accessible cable sections, suitable man carrying equipment is required. Nondestructive inspections for external and, especially, internal defects of accessible cables, cable sections or bundles are possible with electromagnetic inspection devices. The electromagnetic inspecction of cables is today a standard, based on a mature technology. Present instruments can be used for cables up to 175 mm diameter. But it is very important that the use of these instruments is controled by experts and interpretations of the recorded signals are done by the same experts. To assess the condition of sections near the anchorages and saddles, electro-optic systems can be useful. For certain types of cable connections, specialized ultrasonic inspections are possible. For a final evaluation of all findings, experience is important. Structural details must be known, especially for the first inspection of a structure. Only a thorough understanding of material aging, fatiguing, and other deterioration processes will allow a well-founded appraisal of the condition and safety of cable bridges.

Fig. 11: Corrosion under an undestroyed corrosion protection, detected by EM-inspection