Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 68 (1993)

Artikel: Expert system for the appraisal of structures
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DOI: https://doi.org/10.5169/seals-51868

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.

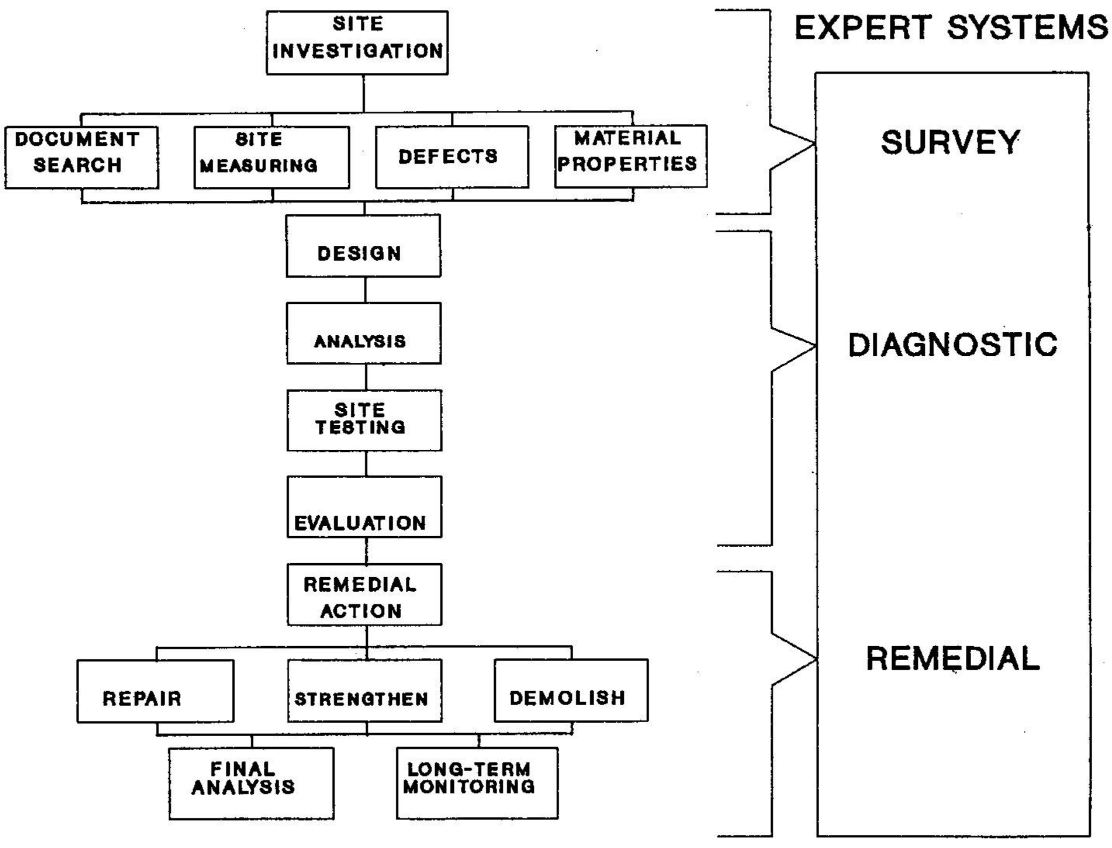

Fig. 1 Process of Appraisal

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].

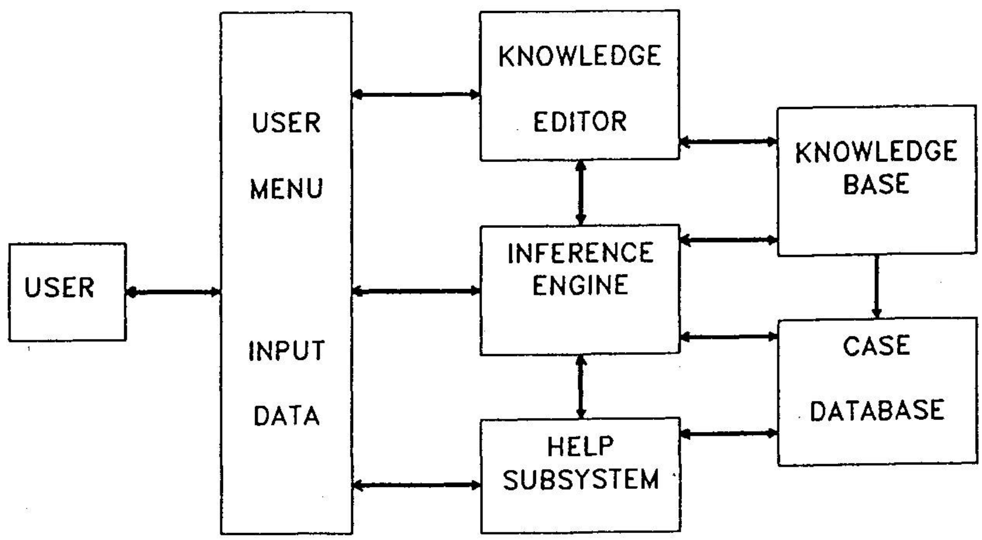

Fig 2. Typical Expert System Modules

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.

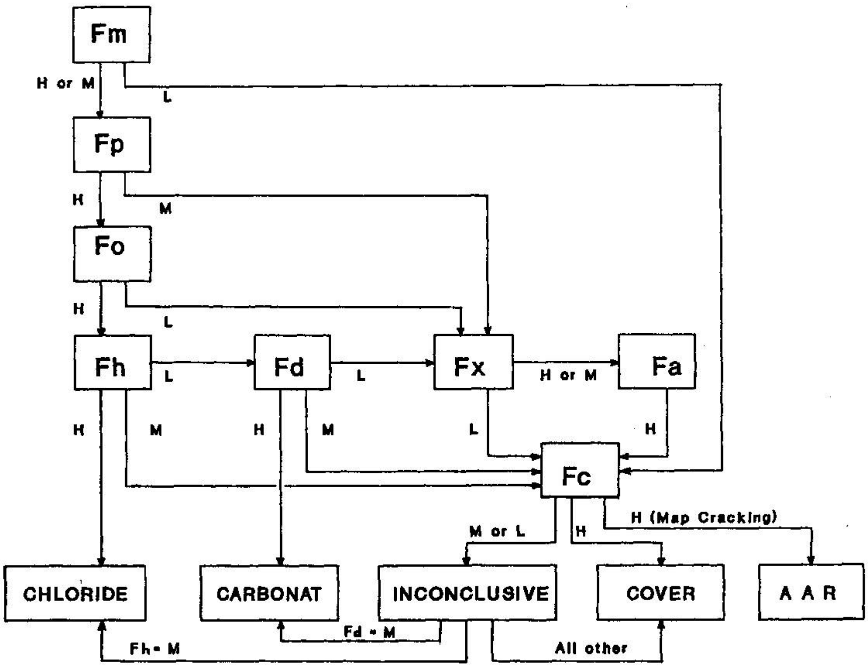

Fig 3. Logic Decision Diagram

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.

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