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A fuzzy expert system for diagnosis assessment of reinforced concrete bridge decks

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Abstract. The lack of safety of bridge deck structures causes frequent repair and strengthening of such structures. The repair induces great loss of economy, not only due to direct cost by repair, but also due to stopping the public use of such structures during repair. The major reason for this frequent repair is mainly due to the lack of realistic and accurate assessment system for the bridge decks. The purpose of the present research was to develop a realistic expert system, called Bridge Slab-Expert which can evaluate reasonably the condition as well as the service life of concrete bridge decks, based on the deterioration models that are derived from both the structural and environmental effects. The diagnosis assessment of deck slabs due to structural and environmental effects are developed based on the cracking in concrete, surface distress and structural distress. Fuzzy logic is utilized to handle uncertainties and imprecision involved. Finally, Bridge Slab-Expert is developed for prediction of safety and remaining service life based on the chloride ions penetration and fick's second law. Proposed expert system is based on user-friendly GUI environment. The developed expert system will allow the correct diagnosis of concrete decks, realistic prediction of service life, the determination of confidence level, the description of condition and the proposed action for repair.

Keywords: reliability and safety; computer; concrete; durability; service life; environment condition; software.

1. Introduction

Concrete deterioration and corrosion of reinforced concrete structures is a major problem in the hot and corrosive environment of the Persian Gulf region. The lack of safety of bridge deck

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structures causes frequent repair and strengthening of such structures. The repair induces great loss of economy, not only due to direct cost by repair, but also due to stopping the public use of such structures during repair (Abideen and Eldin 1999). The major reason for this frequent repair is mainly due to the lack of realistic and accurate assessment system for the bridge decks. Therefore, it is necessary to establish a reasonable expert system which can predict realistically the condition and status of concrete bridge decks, including the determination of remaining service life.

There are several researches in application of fuzzy expert system in order to develop the evaluation of bridge performance, the suggestion of maintenance strategy, the data store of inspection and bridge specifications. The framework of a fuzzy expert system has been constructed to diagnose bridge damages so as to provide bridge designers with valuable information about the impact of design parameters on bridge deterioration (Zhao and Chen 2001, 2002). The fuzzy expert system condition rating method has been developed practically based on results of existing inspection methods and tools. The parameters of the model are selected as fuzzy inputs with membership functions found from some statistical data and then the fuzziness of the condition rating is calculated by the fuzzy arithmetic rules inherent in the fuzzy expert system (Kawamura and Miyamoto 2003). The fuzzy set theory has been employed to link the bridge deck damage with its appearance (Furuta *et al.* 1996). The fuzzy mapping formalism has been used to estimate the remaining life and soundness of concrete bridges (Kushida *et al*. 1997). A fuzzy approach which combined the probability theory and the fuzzy reasoning was employed to assess bridge damage levels and their causes (Lee *et al.* 1999). Some rule-based expert systems for diagnosis assessment of concrete structure have been developed. Table 1 lists the existing expert systems developed for concrete assessment and rehabilitation (Fazel Zarandi 2003) and compares with Bridge Slab-Expert.

This paper present a realistic fuzzy expert system, called Bridge Slab-Expert which can evaluate reasonably the condition as well as the service life of concrete bridge decks, based on the deterioration models that are derived from both the structural and environmental effects. The diagnosis assessment of deck slabs due to structural and environmental effects are developed based on the cracking in concrete, surface distress and structural distress. It is achievable by hybrid application of subjective judgments and objective measurements. Subjective data is the result of the visual inspection and objective data is obtained after conduction of a relatively simple and practical nondestructive testing method for corrosion measurement. It is believed that hybrid encoding of observed symptoms into condition rating through imprecise and inaccurate subjective judgments with objective evaluation and interpretation of the NDT results is possible to create a fuzzy

Table 1 Expert systems for concrete assessment and rehabilitation

Expert System	Environmental assessment	Structural assessment	Repair	Rehabilitation	Prototype	Operational
Crack	X				X	
Bridge Rating Expert System	X				X	
Cracks	X				X	
Expear	X		X	X		
Pavement Expert	X				X	
Paver	X		X	X		X
Repcon	X				X	
Bridge Slab-Expert	X	X	X		X	

inference system which is a good tool to guess the condition rating practically. The roles of the expert system in this software are to describe the design and implementation considerations of an expert system tool to aid field inspectors in determining the causes of distress in concrete structures. This system is a valuable tool in automating the acquisition of field information, in presenting a hypothesis on how known distresses relate to cite specific problems, in preserving the knowledge of experts and in providing a record of the condition of structures at different ages. It also provides much needed guidance for practitioners while serving as a decision support system for other experts and specialists in the field. The developed expert system will allow the correct diagnosis of concrete decks, realistic prediction of service life, the determination of confidence level, the description of condition and the proposed action for repair.

2. Deterioration mechanism in concrete bridge structures

The cracks can be due to several reasons. Plastic shrinkage and settlement cracks occur within the first hour of casting concrete. Former results in disintegration of concrete, while the latter causes loss of bond to bars and exposure of reinforcement. Early thermal movement cracks occur within the first few weeks due to excessive temperature variation. Drying shrinkage cracks take from a few weeks to a few years for development. All these cracks create paths for seepage and leakage and ingress of deleterious materials. Therefore, Cracks due to corrosion can cause spalling and lead to rapid deterioration of concrete as shown in Fig. 1 (Raina 1994).

The concrete decks on multi-girder bridges are subject to shrinkage as well as wheel loads. The shrinkage strains are usually restrained due to the longitudinal girders and causes tensile stresses in the concrete decks (Basheer *et al.* 1996). On the other hand, the wheel loads induce tensile stresses adjacent to the wheels due to the direct application of concentrated wheel loads. Therefore, the combined longitudinal tensile stresses on the decks due to shrinkage and wheel loads will induce parallel transverse crack as shown in Fig. 2 (Vagiotas 2003). These transverse cracks will increase more until they are stabilized. These transverse cracks will also cause the deck slab as a set of one-way beams. After transverse cracking, the further application of wheel loads causes longitudinal bottom cracking for the beams and leads to beam-type failure eventually. This type of beam failure may also cause punching failure (Oh *et al.* 2005).

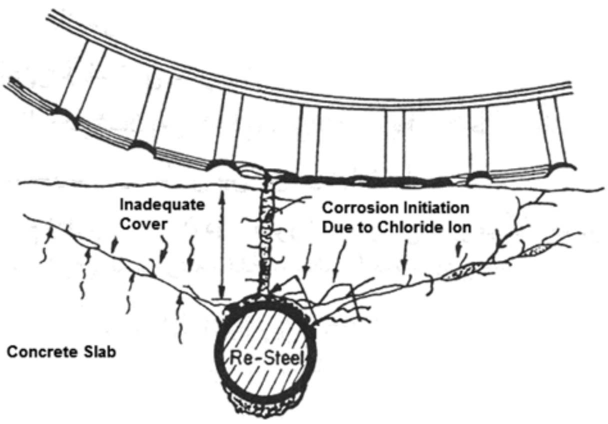

Fig. 1 Rapid deterioration due to expansion of corrosion cracks (Raina 1994)

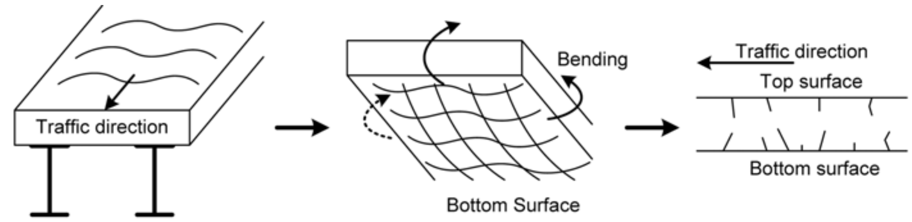

Fig. 2 Deterioration mechanism of deck slab due to cracking (Oh *et al*. 2005)

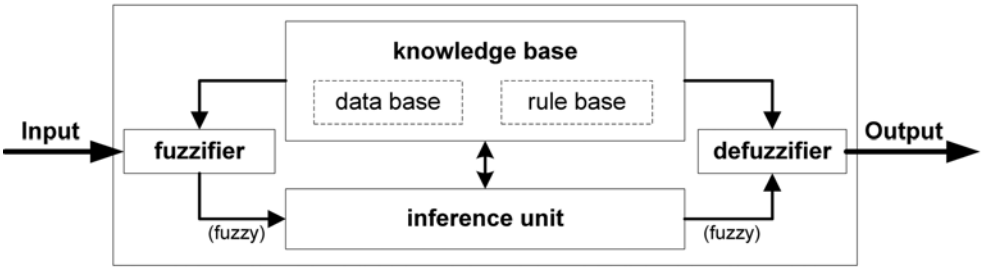

Fig. 3 Fuzzy expert systems perform fuzzy reasoning

3. Fuzzy expert systems

A fuzzy expert system is an expert knowledge-based system that contains the fuzzy algorithm in a simple rule base. In this system, the knowledge, encoded in the rule base, is originated from human experience and intuition and the rules represent the relationships between the inputs and outputs of a system (Siler and James 2005). A fuzzy expert system is comprised of four constituents: fuzzifier, knowledge base, inference engine and deffuzifier (Fig. 3):

The Fuzzifier performs fuzzification, which is 'to convert real numbers of input into fuzzy sets.'

The knowledge base includes a database and a rule base. Database consists of 'membership functions of the fuzzy sets', whereas the rule base includes 'a set of linguistic statements in the form of IF-THEN rules with antecedents and consequents, respectively, connected by AND operator (other operators such as OR, and NOT may be used).'

The inference engine that forms the core of a fuzzy expert system utilizes IF-THEN rules included in the rule base to deduce the output through fuzzy or approximate reasoning. The approximate reasoning procedure is to develop conclusion from a set of IF-THEN rules along with some specified conditions (Durkin 1994).

The defuzzifier defuzzifies the fuzzy output elicited by the inference engine through converting it to a real number domain. The centre of area (COA) is the most popular defuzzification method (Siler and James 2005).

4. Description of bridge slab-expert

Bridge Slab-Expert is a fuzzy expert system that is a computer program using Artificial Intelligence techniques, which involve human knowledge and experience in solving difficult problems that

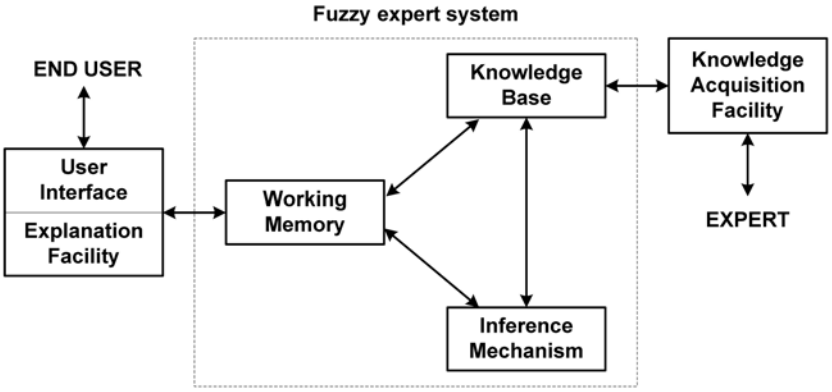

Fig. 4 Components of bridge slab-expert

would otherwise be solved by an expert in a longer time. Several factors affect the system architecture for knowledge-based systems (Papadakis *et al.* 2007). These factors usually depend on the particular application domain, the procedure of direction through the system in solving problems, the software tools (knowledge-based environment, graphical user interface builders and database) and programming language used. Fuzzy expert system of Bridge Slab-Expert comprises three main components, the knowledge base, the inference mechanism and the working memory. The knowledge base and inference engine is engaged by the knowledge system in order to consider the problems and finally to recommend a conclusion. The working memory of the system is used as temporary storage for facts discovered during a consultation. Its content alters dynamically and comprises information provided by the user about the specific information derived by the system. Other development facilities include an user interface, an explanation facility, a knowledge acquisition facility, debugging and help facilities and knowledge base editors. Bridge Slab-Expert components are shown in Fig. 4.

4.1. Bridge slab-expert inference procedure

The Bridge Slab-Expert inference procedure is divided into two parts. The main implementation part includes input and reporting system, expert system development environment, database management system and the evaluation management system. The second part is the user-interface. Architecture of Bridge Slab-Expert is shown in Fig. 5.

4.1.1. Input and report system

The input comprises a full description of the user requirements such as structure and component types, structural design and construction types and visual inspection data such as distress and symptom categories. In this part the help option in each section provides assistance for users in the form of pictures, text and/or combination thereof.

The reporting system summarises the consultation result in the form of a visual edit screen. These results comprise the conclusion from the expert system including causes and effects of distress, repair recommendation from the database and conclusions from the evaluation process.

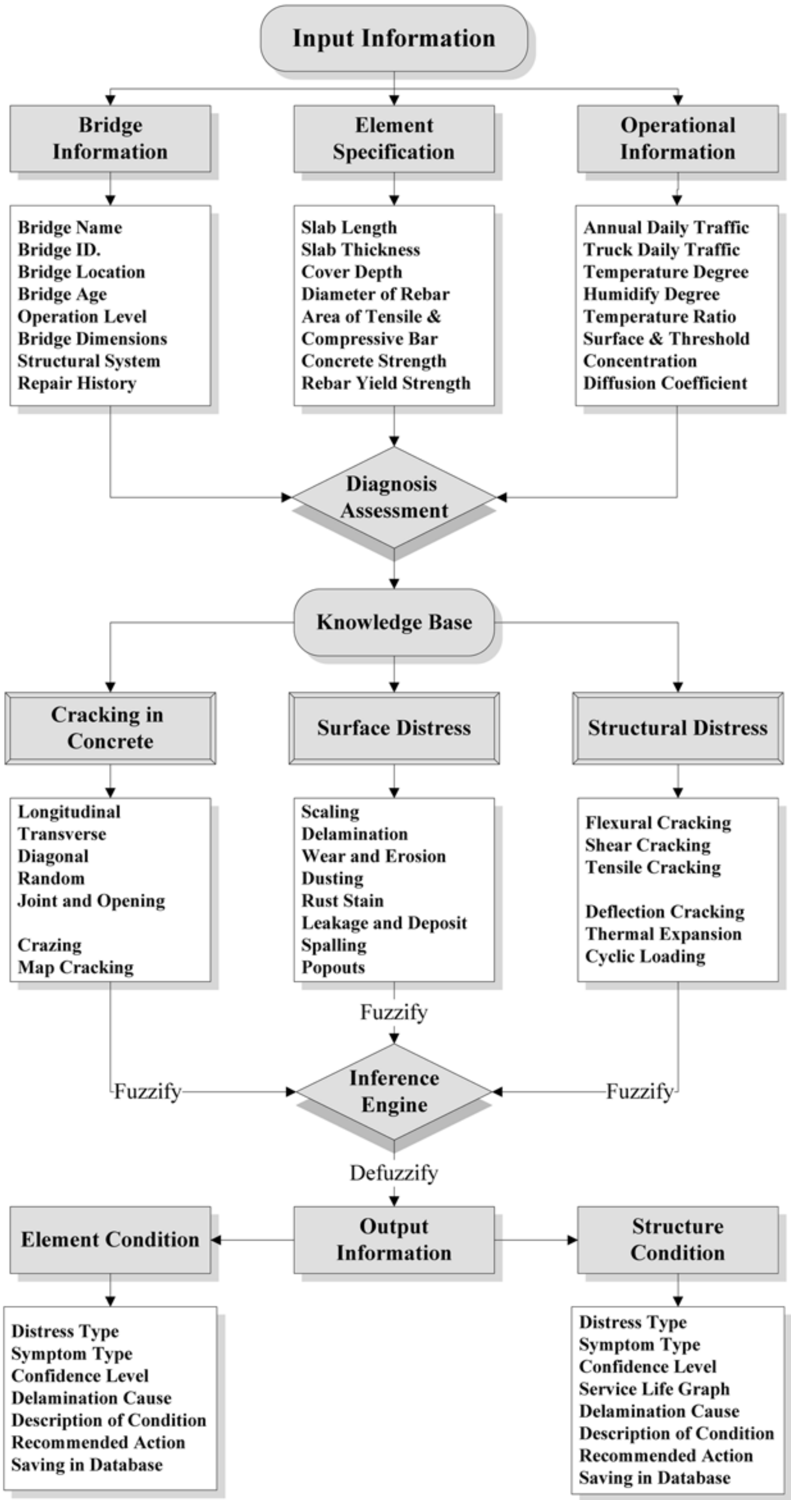

Fig. 5 Architecture of bridge slab-expert

4.1.2. Expert system development environment

All consultation modules are programmed by Visual Basic which is a commercially available programming language that relies on a graphical user interface to modify code. It can be run under the Windows. The modules are integrated into the Visual Basic Graphic User environment through the Visual Basic Controls. In this control there exist procedures which are called by Bridge Slab-Expert Inference when the application requires data from the database or needs to send data to the application. These procedures control the initializing and termination of system consultation. The Bridge Slab-Expert consultation module includes three knowledge bases: cracking in concrete, surface distresses and structural distresses.

4.1.3. Database management system

The Bridge Slab-Expert database is developed using Microsoft Access which a relational database management system is running within Microsoft Windows. This user-friendly software is developed to run on a personal computer and a user interface is provided in the form of visual edit screens which embody the Visual Basic programming language. Microsoft Access database was linked to Visual Basic through the data control in cases where the data did not require any subsequent manipulation. Some databases were linked to the application through the Structured Query Language (SQL) code in cases where there was needs to manipulate the data. The database can be accessed by the user independently of the expert system.

4.1.4. Evaluation management system

The evaluation of concrete is implemented in the form of visual edit screens which embody the Visual Basic programming language and Matlab software. Mamdani fuzzy model has been chosen to be employed through using Fuzzy Logic Toolbox of Matlab software version 7.4.0 (R2007a). The assessment procedures of concrete structures that enable the user to consider the current condition of the structure and its components are the main objective of an evaluation management system. These procedures are expressed as fuzzy terms using conclusion from a set of IF-THEN rules along with some specified conditions. Finally, a confidence level (CL) is taken the best recommended action in the repair and maintenance management.

4.2. The user-interface

The user-interface is an important component of the computer software responsible for the interaction with the user and is fundamental to the effectiveness of the program in fulfilling its primary objectives. In view of this, the Bridge Slab-Expert user-interface is designed to make the program flexible, easy to learn and use and it contributes to the success of the program when carefully designed. It also supports the explanation facility which provides for concise and helpful responses to users queries and allows the user to interact with the system to seek explanations.

5. Bridge slab-expert knowledge bases

The ability of an expert system to solve a problem has been observed to increase with the extent of its domain knowledge. Undoubtedly the most demanding phase of developing an expert system is obtaining and representing relevant knowledge.

Bridge Slab-Expert consists of three knowledge bases, each of which contains information on the

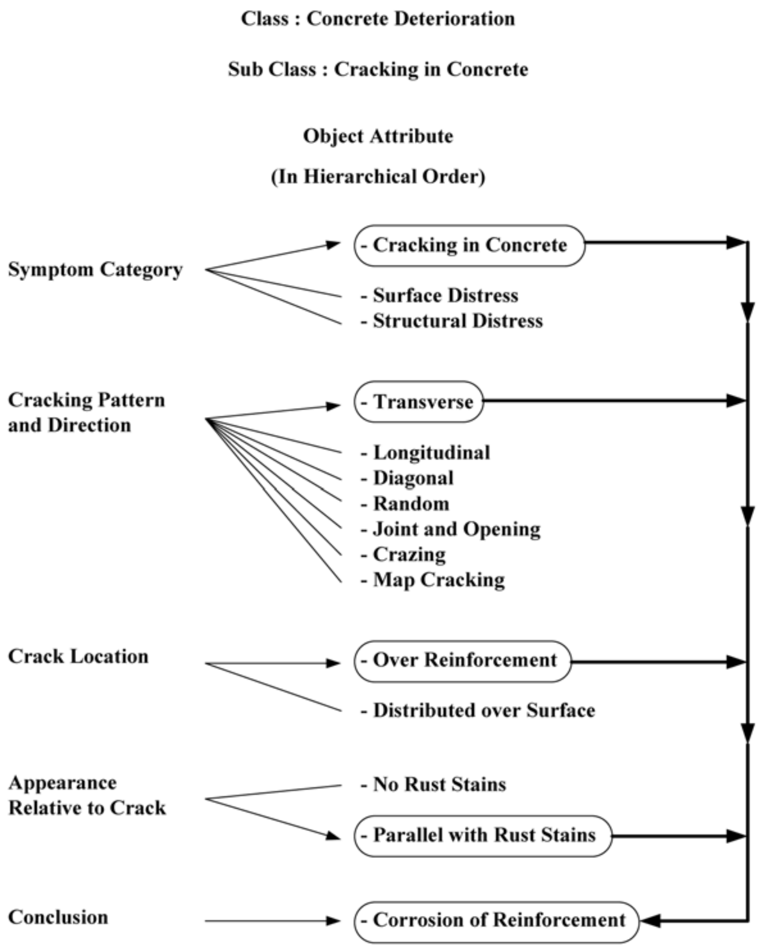

Fig. 6 Representation of firing the rules and deducing the output through the diagnostic trees

various types of distress in concrete structures. The required knowledge for diagnosing the concrete distresses is formulated as production rules (IF…THEN) and procedures and is incorporated in the knowledge base structure. These are typical forms of code in conventional programming languages.

The rules are organized on the diagnostic trees developed during the knowledge acquisition process and are arranged in a manner that provides a fast and accurate information flow. The rule organization is performed by the following steps:

- The knowledge is represented in diagnostic trees during the knowledge acquisition process. The diagnostic tree indicates how the knowledge is linked together and how the rules are written and organized.
- The rule numbers are assigned in the order which they are created.
- The rules are further arranged by assigning the Type and Symptom variables are shown in Fig. 6. These variables control the sequence in which the rules are carried out. The variable Symptom in this rule declares what symptom category has been considered while the Type variable is used to assign the value of distress type such as either longitudinal or diagonal crack in cracking in concrete category.

- The results as a message are assigned based on its order of appearance within the diagnostic tree.

The rules in the Bridge Slab-Expert knowledge bases provide associations between observed bridge conditions and damage causes. They are created by a rule generation algorithm that can convert crisp training data into fuzzy statements. The training data is collected from bridge inspection records and formalized into standard vectors. In the operational mode, the system reads a state vector of observed bridge condition and the inference engine performs damage cause implication through evaluation of the rules. The output of this implication procedure is a linguistic variable that describes the possible damage cause with a confident degree. This linguistic variable can be defuzzified by the explanation facility if a crisp output is desired (Moodi 2001). This system is implemented through the developments of several Matlab modules, which are discussed in details in the following sections.

5.1. Cracking in concrete knowledge base

The Cracking in Concrete knowledge base has been developed for identifying the probable cause of cracks in concrete based on their shape and pattern, density and location. The seven types of crack are selected because they comprise the most persistent manifestations of premature

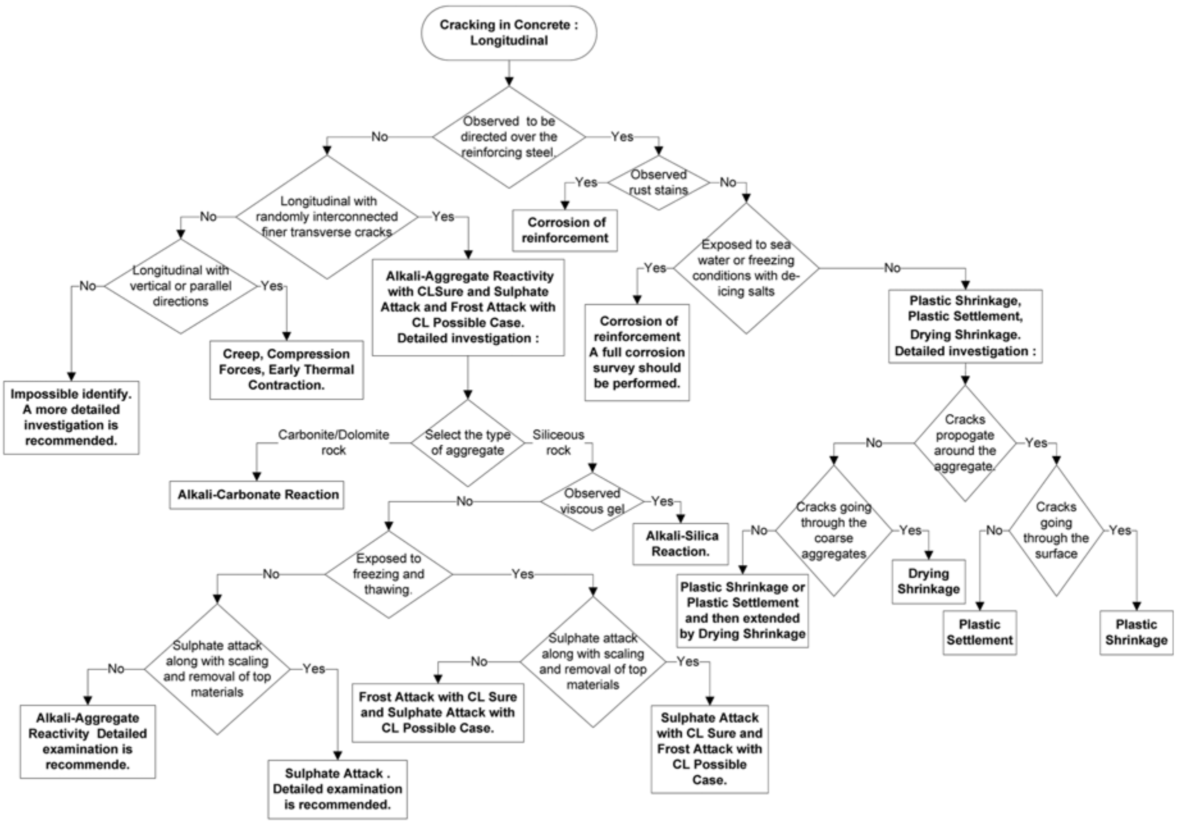

Fig. 7 Diagnostic tree for representing of the knowledge of longitudinal crack

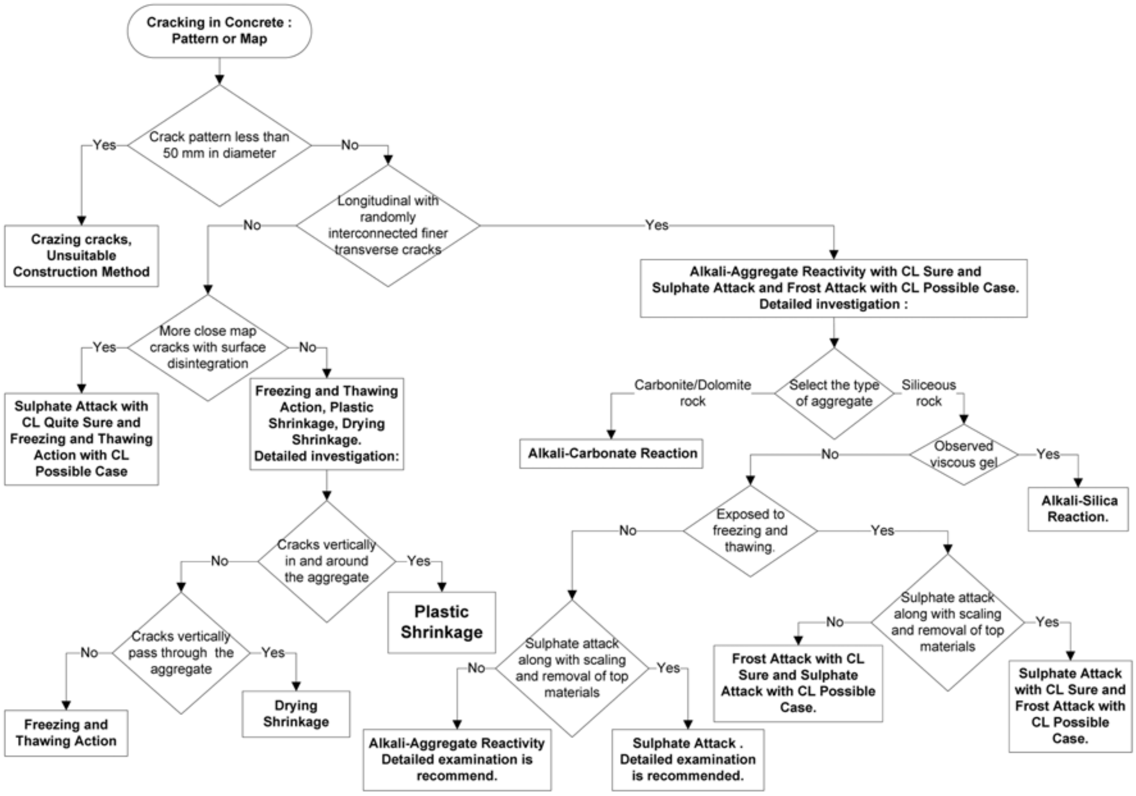

Fig. 8 Diagnostic tree for representing of the knowledge of pattern or map crack

impairment of concrete. Knowledge contained in the system is obtained from codes of practice (ACI, BS 8110, BS 5328, EN, RILEM 1110-2-2002), textbooks, experts in the field, photographs taken of actual concrete failures and the classification of the failures into the database format.

The following definitions summarize the main forms of crack covered by the Cracking in Concrete knowledge base:

- Longitudinal and generally straight
- Diagonal
- Transverse
- Random
- Cracks at Joint, Edge and Opening
- Pattern or Map
- Crazing

The first step in representing this knowledge base is the creation of diagnostic (hierarchical) trees. During the development of cracking in concrete knowledge base, its knowledge was partitioned into seven types of crack, each dealing with a major distress problem (Miyamoto 2000).

Diagnostic trees for knowledge of cracking in concrete are illustrated in Figs. 7-9. Then the facts are expressed in the form of fuzzy rules and procedures. Within the diagnostic tree of cracking in concrete, several questions are asked in the form of linguistic variable concerning the shape and geometry of crack, location, direction and appearance. The fuzzy inference engine searches for

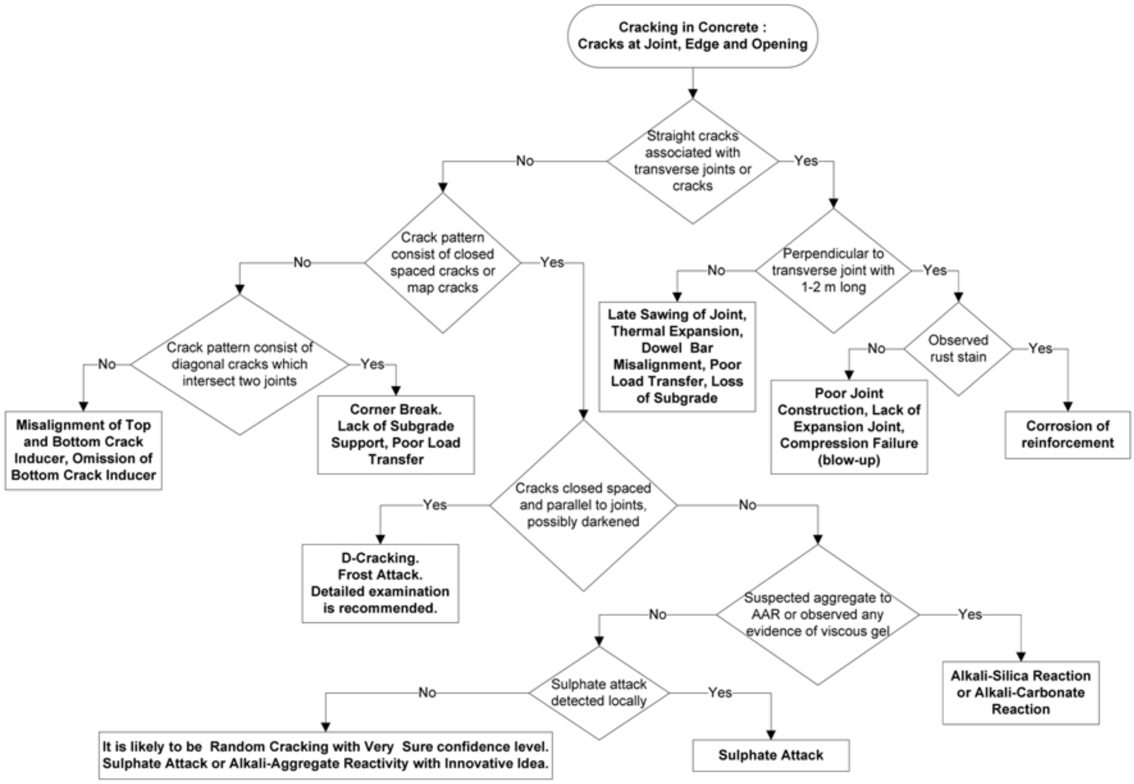

Fig. 9 Diagnostic tree for representing of the knowledge of crack at joint, edge and opening

answers by initiating one or more rules within the cracking in concrete knowledge base. The rules are evaluated and recommendations are given based on the current state of the crack.

5.2. surface distresses knowledge base

Structural impairments of concrete structures are shown in the form of various distresses on the concrete surface. In evaluating the existing condition of concrete structures, it is important to define and describe the distresses objectively and consistently. To achieve this objective, the most persistent manifestations of surface distresses in concrete are chosen for creating the surface distress knowledge base. The surface distress knowledge base contains nine different types of surface distress. Knowledge contained in the system is obtained from codes of practice (ACI, BS 8110, BS 5328, EN, RILEM 1110-2-2002), textbooks, experts in the field, photographs taken of actual concrete failures and the classification of the failures into the database format. The following distresses can be chosen as a main visual distress symptom in the concrete surfaces covered by surface distress knowledge base:

- Scaling, disintegration and removal of materials
- Spalling and popouts
- Joint related spalling or faulting
- Honeycombing

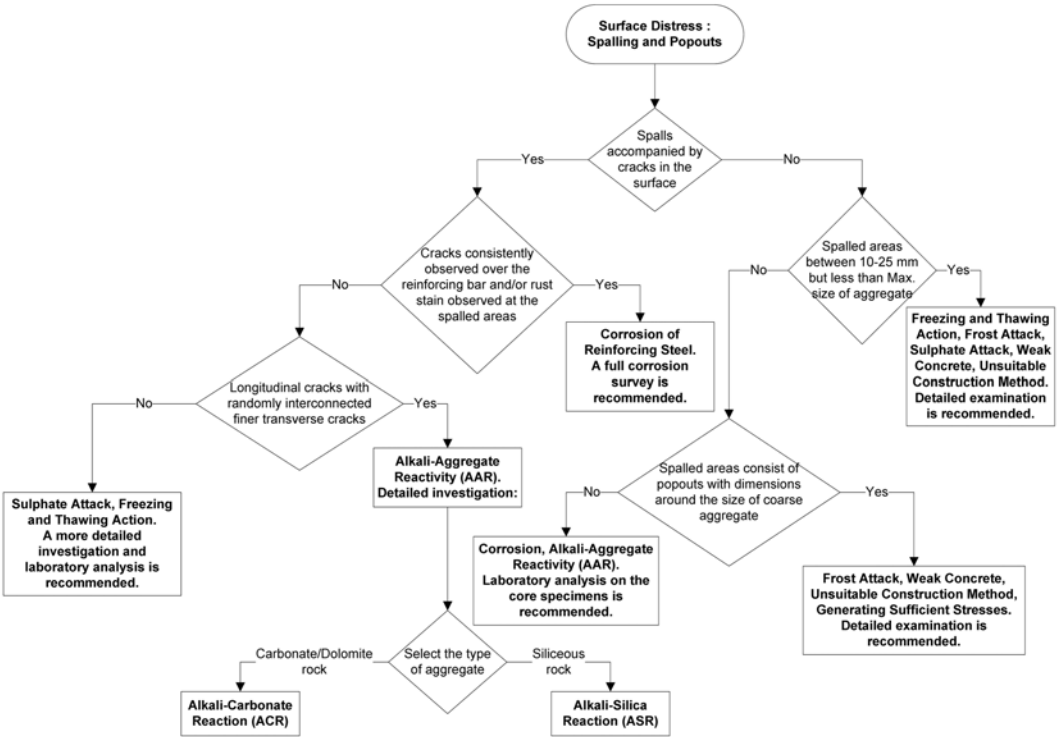

Fig. 10 Diagnostic tree for representing of the knowledge of spalling and popouts

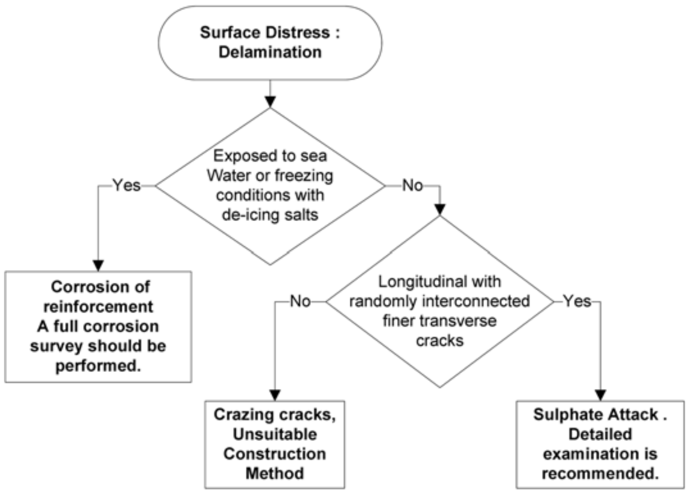

Fig. 11 Diagnostic tree for representing of the knowledge of Delamination

- Pothole
- Dusting
- Discolouration and efflorescence
- Polishing of aggregates
- Wear and Erosion

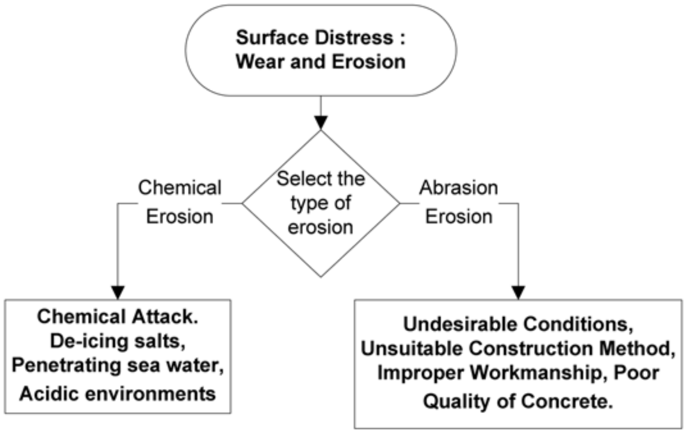

Fig. 12 Diagnostic tree for representing of the knowledge of Wear and Erosion

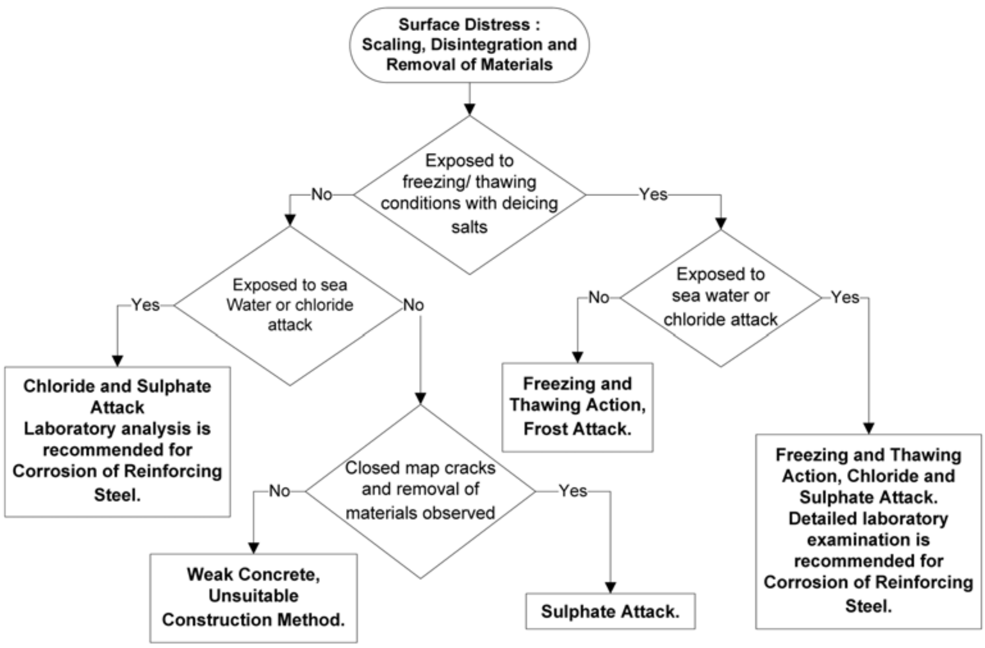

Fig. 13 Diagnostic tree for representing of the knowledge of Scaling and Disintegration

In developing this prototype knowledge base, the diagnostic trees served as the vehicle for communication between the experts who interpreted and organised the knowledge in a hierarchical structure and the knowledge engineer who initially record the knowledge into a question-and-answer sequence form along with a network diagram. Diagnostic tree for representing the knowledge of Spalling and popouts, Delamination, Wear and Erosion, and Scaling and Disintegration are shown in Figs. 10-13.

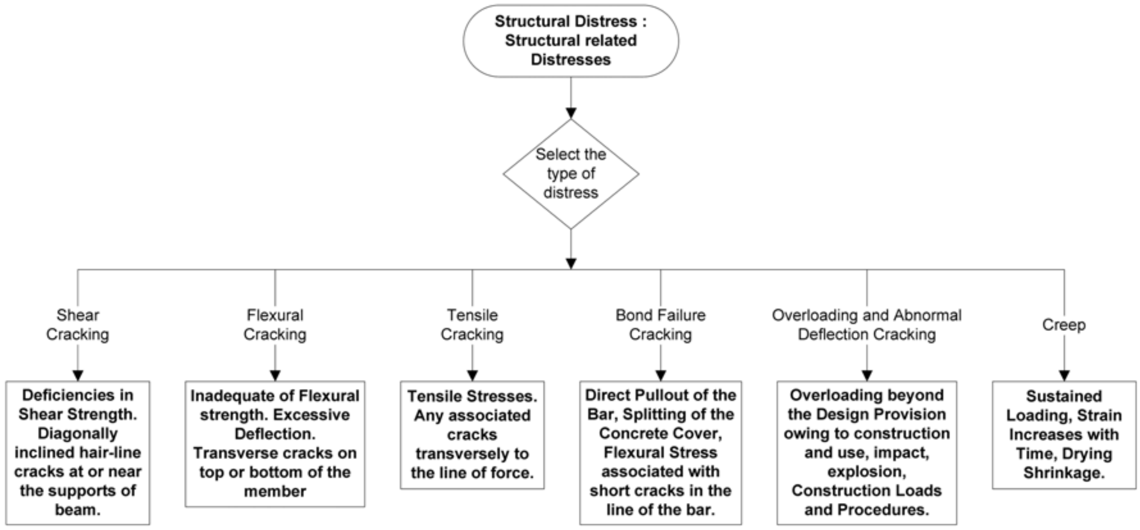

Fig. 14 Diagnostic tree for representing of the knowledge of structural related distresses

5.3. Structural distresses knowledge base

Many other factors may contribute to or cause the impairment of concrete structures. These are described as Structural distresses in this research and are presented in the Structural distresses knowledge base. These forms of distress are as follows:

- Flexural Cracking
- Shear Cracking
- Tensile Cracking
- Deflection Cracking
- Thermal Expansion
- Cyclic Loading

Diagnostic tree for representing the knowledge of structural related distresses is shown in Fig. 14.

6. The confidence level for the evaluation of concrete

In this section, the development of the framework of a fuzzy inference system is presented. One objective of the Bridge Slab-Expert is to create assessment procedures that will allow the current condition of the structure, and its components to be expressed numerically to take the best recommended action in the repair and maintenance management.

6.1. The evaluation procedure

Once the condition of the structure is understood and documented, the next step in the maintenance management process is to initiate action to correct unsatisfactory conditions and to begin planning for future maintenance and repair needs. For this purpose, a fuzzy inference system for the condition of concrete in a structure would make possible the determination of which components within a structure most merit repair. The fuzzy rules provide associations between observed bridge conditions and damage causes. They are created by a rule generation algorithm that can convert crisp data into fuzzy statements. The output of this implication procedure is a linguistic variable that describes the possible damage cause with a confident degree. This linguistic variable is defuzzified by the explanation facility to crisp output defined as Confidence Level (CL). The Evaluation Confidence Level extends from 0 to 100, with 0 representing Very Poor condition and 100 representing Excellent condition. The Confidence Level is divided into Minor, Moderate and Major zones. The criteria for the evaluation of a concrete structure is shown in Table 2.

The Confidence Level prescribed here applies to concrete structures in general. The fuzzy inference system described allows the distress level to be determined by visual inspection using limited equipment such as binocular, cover meter and ruler. Values in each parts of progressing are properly interpreted as representing the current conditions found at the time the structure was inspected and rated. The rating is related to structural integrity and serviceability of the structure. The Confidence Level system is not intended to replace the detailed investigation needed to fully document structural deficiencies, to identify their causes and to formulate plans for correcting them. An extended investigation comprising detailed investigation and analysis, and engineering evaluation should be made when the Confidence Level is less than 50.

6.2. Distress level and description

Distress level for various distress categories that tend to result in cracking in concrete, disintegration and scaling, spalling and delamination are shown in Tables 3 to 6.

Table 2 The confidence level for the evaluation of concrete structure

Zone	Confidence Level	Description	Recommended Action
Minor	95 - 100	**Excellent:** No noticeable impairments.	Prompt action is not required, but periodic investigation is recommended. In some cases, protection might be needed.
	85 - 94	**Very Good:** Barely noticeable impairments. Some ageing or dusting may be visible.	
Moderate	70 - 84	**Good:** Clearly noticeable impairments. Only minor defect, damage and deterioration are evident.	Detailed investigation and economic analysis of repair alternatives are recommended. In some cases, appropriate repair and protection methods will be needed.
	50 - 69	**Fair:** Moderate impairments. Some defect, damage and deterioration are evident, but concrete remains serviceable.	
Major	30 - 49	**Poor:** Severe impairments in at least some major components of the structure have been occurred. Concrete remains serviceable.	Detailed investigation and an engineering evaluation should be made to determine the demand for repair, replacement strengthening and stabilization. Safety evaluation is recommended.
	0 - 29	**Very Poor:** Very severe and extensive impairments in most components of the structure. General failure or a complete failure of structural components.	

A number of crack categories are provided including individual cracks such as longitudinal, transverse, diagonal and random, and such pattern cracking as crazing and map cracking. Distress levels for crack categories shown in Table 3 are dependent on crack width and depth. By comparing ACI, BS 8110, BS 5328, EN and RILEM reports with U.S. Army Corps of Engineers 1110-2-2002, crack width is classified into Very Fine (< 0.25 mm), Fine (0.25-1.0 mm), Medium (1.0-2.0 mm), and Wide (> 2.0 mm). The three categories generally used to describe the depth of cracking are Surface and Shallow (up to 10 mm), Deep (10-20 mm) and Through (> 20 mm). This category is based on the author's research, the U. S. Army Corps of Engineers recommendations and the size of coarse aggregates (19-25 mm) used in the concrete. Distress Level is classified into Very Slightly (VSl), Slightly (Sl), Moderate (M), Severe (Se), Very Severe (VSe). Each distress level for various distress categories is represented base on scale of deduction as fuzzy number.

Surface distress is categorized into disintegration, scaling, spalling and delamination. A number of concrete volume-loss categories shown in Table 4 is provided comprising spalling, popouts and pitting, and joint related spalling.

A number of concrete surface-loss modes such as those shown in Tables 5 is listed including scaling, dusting, leakage and deposits, wear and erosion, and rust stain. Descriptions of surface appearance are provided by comparing ACI, BS 8110, BS 5328, EN and RILEM reports with U.S. Army Corps of Engineers 1110-2-2002. Distress levels depend on estimated depth, extent and

Table 3 Distress level for cracking in concrete

Class: Cracking in Concrete	Subclass: Type of Crack	Distress Level	Width of Crack			
		Depth of Crack	Very Fine	Fine	Medium	Wide
Individual	Longitudinal	Surface	VSl	VSl	Sl	M
		Deep	Sl	M	Se	VSe
		Through	M	Se	VSe	VSe
	Transverse	Surface	VSl	VSl	Sl	M
		Deep	M	M	Se	VSe
		Through	Se	VSe	VSe	VSe
	Diagonal	Surface	VSl	VSl	Sl	M
		Deep	Sl	M	Se	VSe
		Through	M	Se	VSe	VSe
	Random	Surface	VSl	VSl	Sl	M
		Deep	Sl	M	Se	VSe
		Through	M	Se	VSe	VSe
	at Joint	Surface	VSl	VSl	Sl	M
		Deep	Sl	M	Se	VSe
		Through	M	Se	VSe	VSe
Pattern	Crazing	Surface	VSl	Sl	-	-
	Map Cracking	Surface	VSl	VSl	Sl	M
		Deep	Sl	M	Se	VSe
		Through	M	Se	VSe	VSe

Table 4 Distress level for surface distresses

Class: Surface Distress	Distress Level	Description
Spalling	Very Slightly	Barely noticeable
	Slightly	Clearly noticeable
	Moderate	Holes larger than popouts
	Severe	Not greater than 20 mm in depth nor greater than 150 mm in any dimension
	Very Severe	Deeper than 20 mm and greater than 150 mm in any dimension
Popouts and Pitting	Very Slightly	Barely noticeable
	Slightly	Noticeable
	Small	Holes up to 10 mm in diameter
	Medium	Holes between 10 to 50 mm in diameter
	Large	Holes greater than 50 mm in diameter
Joint Related Spalling	Very Slightly	Less than 0.6 m long and 0.1 m wide – no loose pieces
	Slightly	As above – pieces loose or missing
	Moderate	More than 0.6 m long – broken into pieces more than 0.1 m wide
	Severe	As above – large pieces missing
	Very Severe	As above but on both sides of joint or cracks

exposure of coarse aggregates.

Structural distresses categorized into Flexural Cracking, Shear Cracking, Tensile Cracking, Bond Failure Cracking, Overloading and Abnormal Deflection Cracking, and Creep. A number of structural crack categories are shown in Table 6.

Due to complexity of environment effects and their unknown combinations, and availability of precise history of structural loading types in inspection, structural distresses evaluated independently from the other distresses. They rule as multiplier coefficient into their following cracking in concrete.

6.3. Fuzzy inference engine module

The fuzzy expert system in cracking of concrete has been designed to have two input variables that are to be catapulted into the inference engine to generate output that is distress level. The two input variables are ‘depth of crack’ and ‘width of crack’. Table 7 represents the input and output variables with their associated fuzzy intervals.

Figs. 15-17 illustrate the membership functions related to the input, depth of crack and width of crack, and output, distress level, variables respectively. The employed rules are originated through the judgments made on the basis of the measurements from the inspections. The specifications of the system are represented in Table 8. Table 9 represents the rules.

Fig. 18 presents a 3D illustration of the developed fuzzy inference system and Fig. 19. Presents a graphical example of the fuzzy computations for longitudinal cracking.

Once the data is obtained software has been developed to compute the confidence level directly from the inspection records. Several types of distress reduce the confidence level according to rules based on the knowledge, experience and opinion of experts. A combined confidence level for each component is calculated by weighting each distress and based on the concrete distress model.

Table 5 Distress level for surface distresses

Class: Surface Distress	Distress Level	Description
Scaling	Very Slightly	Noticeable
	Slightly	Loss of surface mortar, no exposure of coarse aggregate
	Moderate	Loss of surface mortar up to 5 to 10 mm in depth, exposure of coarse aggregate
	Severe	Loss of surface mortar 5 to 10 mm in depth with some loss of mortar surrounding aggregate particles 10 to 20 mm in depth
	Very Severe	Loss of coarse aggregate particles as well as surface mortar surrounding aggregate, generally to a depth greater than 20 mm
Wear and Erosion	Very Slightly	Noticeable
	Slightly	Loss of surface mortar, no exposure of coarse aggregate
	Moderate	Loss of surface mortar up to 5 to 10 mm in depth, exposure of coarse aggregate
	Severe	Loss of surface mortar 5 to 10 mm in depth with some loss of mortar surrounding aggregate particles 10 to 20 mm in depth
	Very Severe	Loss of coarse aggregate particles as well as surface mortar surrounding aggregate, generally to a depth greater than 20 mm
Leakage and Deposits	Very Slightly	Barely noticeable surface discoloration
	Slightly	Noticeable surface efflorescence
	Moderate	Surface material less than 10 mm thick
	Severe	Surface material more than 10 mm thick
	Very Severe	Surface material along with stalactite
Dusting	Slightly	Any area
	Severe	More than 50% of area
Rust Stain	Slightly	Noticeable surface rust staining
	Severe	Surface rust staining along with Cracking

Table 6 Distress level for structural distresses

Width of Crack	Distress Level	Width of Crack			
	Depth of Crack	Very Fine	Fine	Medium	Wide
Flexural Cracking	Surface	1.05	1.1	1.2	1.3
	Deep	1.1	1.2	1.3	1.4
	Through	1.2	1.3	1.4	1.5
Shear Cracking	Surface	1.05	1.1	1.2	1.3
	Deep	1.1	1.2	1.3	1.4
	Through	1.2	1.3	1.4	1.5
Tensile Cracking	Surface	1.05	1.1	1.2	1.3
	Deep	1.1	1.2	1.3	1.4
	Through	1.2	1.3	1.4	1.5

Distress level for various distress categories that tend to result in cracking and in volume loss of concrete were determined from fuzzy inference system. Distress level are subtracted from 100 to established the CI. When multiple distresses occur in a part of the concrete structure, to calculate the

Table 7 The input and output variables with their associated fuzzy intervals

System's variables	Linguistic variables	Linguistic values	Fuzzy intervals
Inputs	Depth of crack	Surface	0-25
		Deep	0-50
		Through	≧20
	Width of crack	Very Fine	0-0.25
		Fine	0-1
		Medium	0.25-2
		Wide	≧1
Output	Distress level	Very Slightly	0-25
		Slightly	0-50
		Moderate	25-75
		Severe	50-100
		Very Severe	75-100

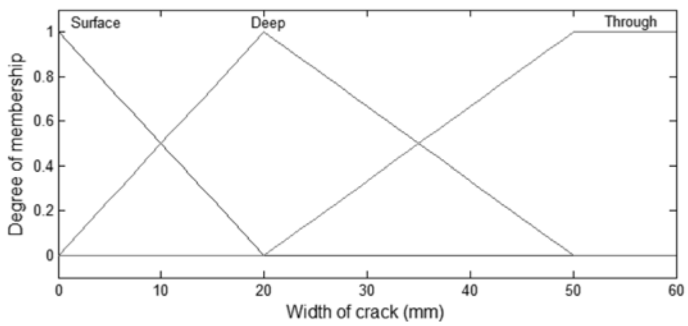

Fig. 15 Membership functions related to width of crack in longitudinal cracking

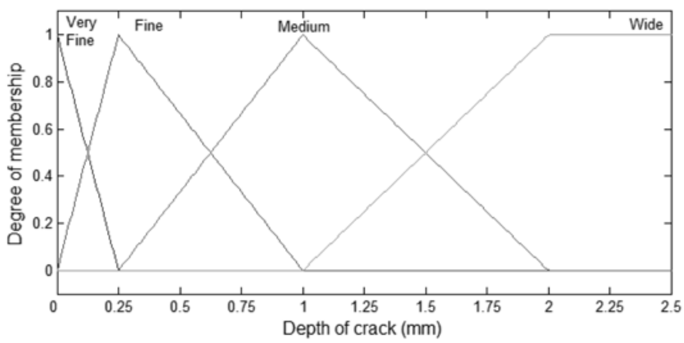

Fig. 16 Membership functions related to depth of crack in longitudinal cracking

CI the five largest distress level (DL), with DL1 the largest value and other values in descending order to the fifth largest, DL5 were considered. The calculation was based on the following equation (Dashmukh 2000):

$$CCL = 100 - [1.0(DV1) + 0.4(DV2) + 0.2(DV3) + 0.15(DV4) + 0.1(DV5)]$$

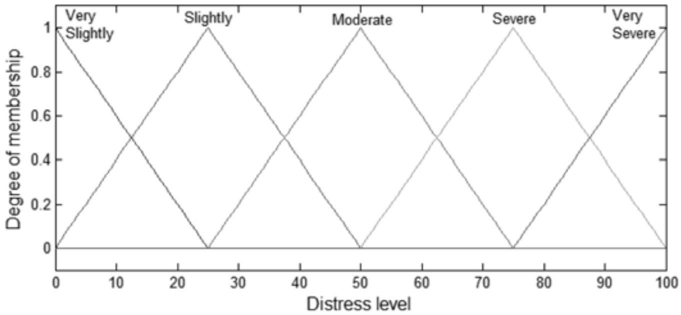

Fig. 17 Membership functions related to distress level

Table 8 Specifications of the inference system

System type	Membership functions' type related to the input variables	Membership functions' type related to the output variable	Fuzzy operator	Implication method	Aggregation method	Deffuzification method
Mamdani	Triangular	Triangular	AND (minimum)	Minimum	Maximum	Centroid

Table 9 System's rules for longitudinal cracking

Rule's No.	Rule	Rule's weight
1	IF depth of crack is Surface AND width of crack is Very Fine THEN distress level is Very Slightly	1
2	IF depth of crack is Surface AND width of crack is Fine THEN distress level is Very Slightly	1
3	IF depth of crack is Surface AND width of crack is Medium THEN distress level is Slightly	1
4	IF depth of crack is Surface AND width of crack is Wide THEN distress level is Moderate	1
5	IF depth of crack is Deep AND width of crack is Very Fine THEN distress level is Slightly	1
6	IF depth of crack is Deep AND width of crack is Fine THEN distress level is Moderate	1
7	IF depth of crack is Deep AND width of crack is Medium THEN distress level is Severe	1
8	IF depth of crack is Deep AND width of crack is Wide THEN distress level is Very Severe	1
9	IF depth of crack is Through AND width of crack is Very Fine THEN distress level is Moderate	1
10	IF depth of crack is Through AND width of crack is Fine THEN distress level is Severe	1
11	IF depth of crack is Through AND width of crack is Medium THEN distress level is Very Severe	1
12	IF depth of crack is Through AND width of crack is Wide THEN distress level is Very Severe	1

The Evaluation Confidence Level extends from 0 to 100 is described in Table 1. The system is designed to be independent of the inspectors. However a combination of the field approach and experience with different inspectors in determining the Confidence Level will influence the quality of their decision. Therefore, a variation of ±10 in the Confidence Level for a structure component can be expected.

Finally, The diagnosis of concrete decks, prediction of service life (Biondini *et al*. 2006), the determination of confidence level, the description of condition and the recommended action for repair, is reported by Bridge Slab-Expert as shown in Fig. 20 and saved in the database of the system.

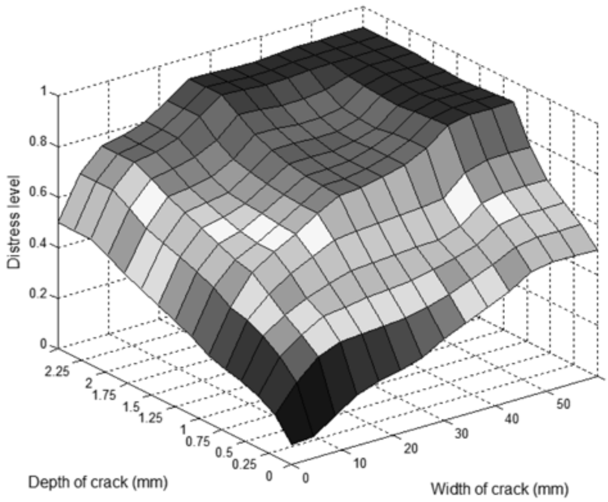

Fig. 18 3D illustration of the developed fuzzy inference system for longitudinal cracking

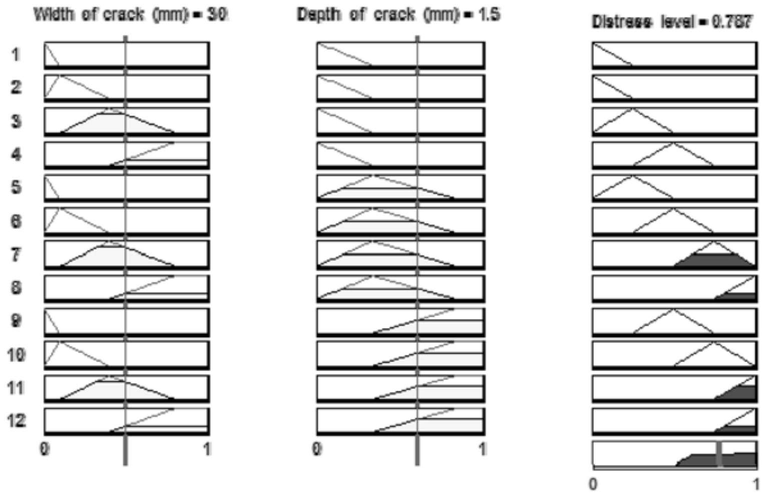

Fig. 19 A graphical example of the fuzzy computations for longitudinal cracking

7. Conclusions

Bridge Slab-Expert is designed to model a true evolution of a field of expertise but allows that expertise to move on in a faster and more structured manner. The methodology can be applied in any area of expertise that is knowledge based. The only impediment to its being extended widely is the initial populating of the knowledge base. Once the system has been established, there is no reason why it should not gathering credibility and value as it evolves. A central feature of the system is the opportunity for information to change status. Finally, Bridge Slab-Expert is developed for prediction of safety and remaining service life. Proposed expert system is based on user-friendly GUI environment and will allow the correct diagnosis of concrete decks, realistic prediction of service life, the determination of confidence level, the description of condition and the recommended action for repair.

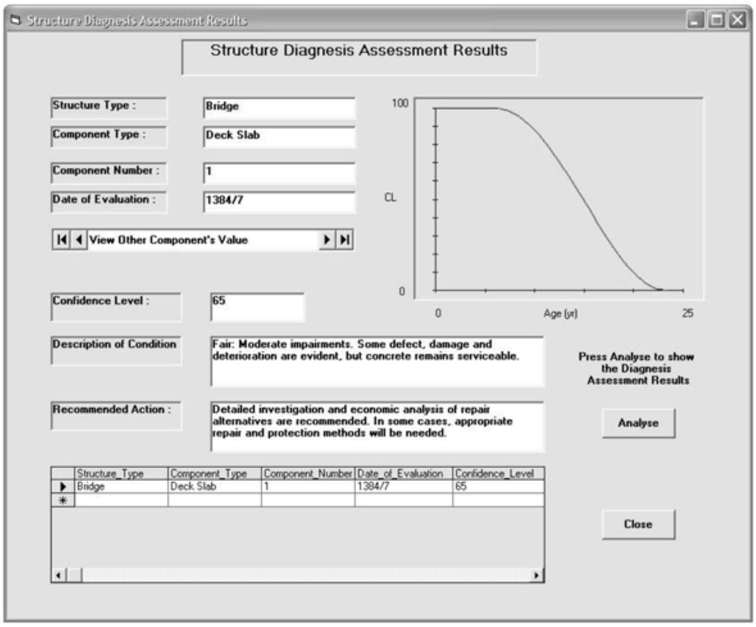

Fig. 20 Structure diagnosis assessment results

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