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Investigation of a management framework for condition assessment of concrete structures based on reusable knowledge and inspection

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Abstract. Managing and reusing knowledge in engineering and construction sectors can lead to greater competitive advantage, improved designs, and more effective management of constructed facilities. The use of Information Technology (IT) in design and construction can exploit strategic opportunities for new ways of integration, sharing and facilitating information and knowledge in any field of engineering. The integrating of separate areas of IT can be used to bring a group of experts and specialists in any field of engineering closer together by allowing them to communicate and exchange information and expertise that facilitate knowledge capture, sharing, and reuse. A lack of an advisory management system and a need to marshal all available data in a common format has indicated the need for an integrated engineering computing environment to investigate concrete repair problems. The research described in this paper is based upon an evaluation management system (EMS) which comprising a database management system (REPCON) alongside visualisation technologies and evaluation system (ECON) is developed to produce an innovative platform which will facilitate and encourage the development of knowledge in educational, evolution and evaluation modes of concrete repair. This allows us to create assessment procedures that will allow the current condition of the concrete structure and its components to be expressed numerically using a confidence level (CL) so as to take the best course of action in the repair and maintenance management. The explained rating system, which is related to structural integrity and serviceability of the structure, allows the confidence level to be determined by visual inspection and the descriptive information and pictures taken from an available REPair of CONcrete (REPCON) database.

Keywords: knowledge management; databases; concrete structures; concrete evaluation; rehabilitation; diagnosis.

1. Introduction

Knowledge Management (KM) is managing the corporation's knowledge through the processes of creating, sustaining, applying, sharing and renewing knowledge to enhance organizational performance and create value (Allee *et al.* 1997, Davenport *et al.* 1998). According to Davenport *et al.* (1998), there are four kinds of knowledge management projects. They are (1) creating knowledge repositories in which knowledge can be retrieved easily. (2) Improving knowledge access to facilitate its transfer between individuals. (3) Enhancing a knowledge environment to conduct more effective knowledge creation, transfer and use, (4) managing knowledge as an asset and concern about how to increase

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the effective use of knowledge assets over time. The concept of knowledge management (KM) is now familiar to the construction industry, and various attempts are being made to develop tools and techniques for the effective management of knowledge in the industry. Most of the consulting organizations used knowledge to speed up the process of providing consulting solutions.

Knowledge reuse is a critical concept for knowledge management. The extent of knowledge reuse can facilitate allocation for knowledge bases, software, hardware, and network resources. The definition of reuse in software engineering is the use of an existing software component in a new context, either elsewhere in the same system or in another system. It is generally said that software reuse is improved productivity and quality, resulting in cost saving (Fujiwara *et al.* 2003). In addition, reuse can guide the choice of knowledge bases and facilitate knowledge management system design. Managing and reusing knowledge in architecture, engineering, and construction firms can lead to greater competitive advantage, improved designs, and more effective management of constructed facilities. However, reuse often fails because knowledge is not captured; it is captured out of context, rendering it not reusable; or there are no formal mechanisms for finding and retrieving reusable knowledge. This paper presents ongoing research on design knowledge reuse that introduces the notion of knowledge in context from a corporate perspective. It is argued that in order for knowledge to be reusable, the user should be able to see the rich context in which this knowledge was originally created and interact with it.

Information Technology (IT) is an important enabler of knowledge sharing and reusing. IT continues to play an important and ever increasing role in the construction process, challenging many traditional working practices and providing construction professionals with new technical and managerial opportunities. IT is the application of systems of information and knowledge to gathering data and creating information that is valuable to users who make decisions. Researchers, software developers and practitioners are now applying Information Technology to automate different parts of the design and construction processes. The nature of construction activity, its structure and its operating environment are fluid and dynamic. This dynamism is growing at an increasing pace; offering proportionately greater strategic opportunities while posing significant threats. The value of knowledge and the status of information change with time and may eventually be of no worth. A principal feature of how design and construction processes have coped these changes has been to strategically exploit Information Technology (IT). The use of IT in design and construction is becoming increasingly sophisticated with object-oriented techniques, virtual reality, expert systems (ES), database management systems (DBMS), case-based reasoning and neural networks among the latest technological advances. These technologies can be used to enhance the integration and sharing of information between the various processes of design and construction (Betts 1999).

Concrete repair is a complex process, presenting unique challenges very different from those experienced in the field of new concrete construction. The impairment of concrete is an extremely complex subject and in most cases, the damage detected will be the result of more than one mechanism (Scott *et al.* 2003 and Raupach 2005). It is important to gain an understanding of the basic causes and mechanisms of the various forms of distress, which may attack concrete. Although impairment of concrete structures is usually a medium to long-term process, the onset of distress and its rate may be influenced by the presence of defects, which have their origin at the time of construction, or in the very early stage of the life of the structure.

Condition assessment of concrete structures is apparently far more difficult than the analysis of design (Cabrera *et al.* 1995, USACE 1995). The concrete assessment involves uncertainties owing to the complexity of impairment mechanisms, availability of information and the heterogeneous nature of the concrete material. When problems are faced with uncertainty and gathering information, assessing consequences and making a decision are also complicated. One of the most important characteristics of successful assessment in all types of organisations is the ability to make the correct decision more often than the incorrect one when confronted with insufficient information.

With respect to the evaluation of structural concrete which is related to structural integrity and serviceability, there is a wide range of IT applications that have been developed for concrete design, condition assessment and repair and rehabilitation of concrete structures. A fuzzy based assessment system for reinforced concrete building structures which estimates the current state of buildings and presents a guide for future maintenance and management was developed (Kim *et al.* 2006). The primary assessment categories include the state of building history, environmental conditions, structural capacity, and durability. Each category consists of a set of sub-criteria. A modular stepwise assessment facilitates efficient assessments and is able to cope with the problem of missing criteria. The assessment criteria are estimated based on visual inspection and simply measured data based on the given criteria. When applied to the actually diagnosed buildings, the proposed system provided results similar to those obtained by experts, and it is expected that this system can be used as an effective maintenance and management tool for reinforced concrete building structures in regular inspection stages.

To assist airport managers, engineers and maintenance personnel in undertaking pavement design, performance, preventive and remedial maintenance and repair, an advisory circular (AC) has been developed by the Federal Aviation Administration (FAA 2003).

The fourth major version of Pontis bridge management system (BMS), a product of AASHTO, continues to support the complete bridge management cycle, including bridge inspection and inventory data collection and analysis, recommending an optimal preservation policy, predicting needs and performance measures for bridges, and developing projects to include in an agency's capital plan. Transportation agencies licensing Pontis use the system in greatly varying ways and frequently have taken advantage of the system's flexibility to customize their implementation of Pontis to meet agency needs. By allowing agencies across

the country to combine their resources, the joint development program provides enormous economies of scale, particularly in comparison to developing and maintaining individual custom solutions. This results in significant cost savings, not only during initial software development, but also throughout the software product life cycle (Thompson *et al.* 1998 and Robert 2003).

In an effort to improve maintenance techniques and practices for such concrete structures as coastal structures, gravity dams, and retaining walls, the U.S. Army Corps of Engineers (USACE) established the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) research program (USACE 2000). Within the REMR program is a group projects dedicated to the development of computerized maintenance management systems for concrete structures. One of the main objectives of the REMR program was to establish a rational, standard procedure for evaluating the physical condition and to create a method for determining numerical condition and performance ratings which, in turn, would be used to produce Condition Index (CI) values for the structure.

A prototype Bridge Management System (BMS) (Miyamoto *et al.* 2000) was developed for deteriorated concrete bridges by evaluating the output results from a bridge rating expert system. The proposed BMS offers various maintenance plans based on a combination of maintenance cost minimization and quality maximization.

A performance index (PI) method is developed for fast and cursory evaluation of the physical condition of concrete bridges (Cabrera *et al.* 1995). This method originally proposed by Cabrera (1988) introduces the concept of quantitative evaluation of concrete performance in order to implement rapid ranking of the overall state of concrete bridges using the result of the observation of signs of distress and weighting scales based on severity and extent. This procedure involves visual inspection of concrete surface or near surface damages which can be described in terms of severity and extent and takes exposure condition into account as modifier.

The other specific prototypes of IT applications for concrete durability, repair and rehabilitation, and condition assessment are known as CRACKS (Kaetzel *et al.* 1989), DURCON (Clifton *et al.* 1985), REMR (USACE 2000), HWYCON (SHRP 1994) and BMS (Orndoff 2003). Most of the existing prototype applications in the field of concrete repair have been restricted to limited amounts of data and have no facility for sophisticated information/knowledge management.

The most important way in which the future design and construction processes will differ from the present will be through a greater measure of integration. Many projects in the future will have greatly improved flows of information between their participants. This will encourage the use of divers technologies to work towards the integrated project database concept. This improved information flow will lead to re-engineered and improved processes of design and construction. It will also enable much greater integration of the process of design, construction and facilities management. The construction and future operation of buildings will be assessable at design stage through integrated IT, based on established information and design standards.

The use of Information Technology (IT) in design and construction has become increasingly sophisticated with database management systems (DBMS) to enhance the integration and sharing of information and expertise for performing condition surveys and quantitative condition assessment. This area of Information Technology (IT) can be used to enhance the interpretation of visual inspections and can often describe failure modes for materials and structures.

An Evaluation of CONcrete (ECON) management system has been developed and is the focus of this paper. The paper explains how a computerised evaluation system can work in collaboration with a database management system called REPCON to describe a proposed system for determining a confidence level (CL). The main objective of this paper is to create uniform procedures for assessing the current condition of structures that numerically rate the condition of the distressed concrete. It will be shown how the procedure developed in this research is related to structural integrity and serviceability of the structure. The ECON is implemented in the form of visual screens, which embody the Visual Basic programming language. The criteria for the evaluation of a concrete structure consist of cracking, disintegration and scaling, and spalling and delamination.

2. Research objectives

The present work is motivated by a need to transfer knowledge and expertise from the research community in the repair of concrete structures and to make that knowledge and expertise available to practicing structural and construction engineers. Although the repair of concrete research programmes have produced a large body of expertise, applying that expertise remains difficult for the inexperienced users. There is a need to provide technology transfer of information with practical guidance from experts and specialists to other practitioners and vice versa. The main objective of the research was to create uniform procedures for assessing the current condition of structures that numerically rate the condition of the distressed concrete. Information on how to conduct an evaluation of the concrete in a structure was developed in a total management system for the repair of concrete structures with sufficient flexibility to allow an inexperienced user to develop the interest in concrete repair technology while at the same time allowing an expert to contribute experience and knowledge towards improving and evolving problem-solving in the field of concrete repair.

3. Modelling variability and simulation

Civil engineers have always had to deal with uncertainty, but they are now expected to do so in more accountable ways. Probability theory provides a mathematical description of random variation and enables the user to make realistic risk assessments. Statistics is the analysis of data, and the subsequent filling of probability models.

Simulation is used to define the performance of public transport systems, to investigate the efficiency of control rules for reservoir releases, to examine the response of structures to extreme events and to investigate the propagation of cracks in offshore structures by structural engineers. The advantages over theoretical results are that simulation can be used in complex situations for which appropriate formulas are not known. The disadvantage is that simulation is far less convenient than an algebraic formula (Metcalfe 1997).

Situations have been considered in which observations are made over a period of time and that are influenced by chance or random effects, not just at a single instant but throughout the entire interval of time or the sequence of times that are being considered. This situation is termed a stochastic process. A stochastic process is a phenomenon that varies to some degree unpredictably as time goes on. A point process is a continuous time model for a stochastic process in which events occur at a point in time. The simplest example is a Poisson process, which is characterized by the Markov property. That is, the probability of an occurrence in the next interval, of arbitrary length, is independent of the time of the last occurrence and of the entire history of the process (Metcalfe 1997, Soong 2004).

4. Generating a model for concrete distress simulation

In the simplest form of model for multiple concrete distress simulation, symptoms of distress, which can be a sign of the damage of concrete, occur as a Poisson process with a rate of λ per unit of time (Fig. 1(a)). Each symptom has a random number (C) of causes associated with it (Fig. 1(b)). For example, longitudinal cracking might be due to corrosion of a reinforcing bar, plastic or drying shrinkage, alkali-aggregate reactivity (AAR) or freeze-thaw damage. Also in the case of the scaling and disintegration of a surface, it might be in association with freezing and thawing, sulphate and chloride attack, unsuitable construction methods or frost attack. The number of causes is generated via a Poisson distribution, specifically (C-1) is a Poisson random variable with a mean of (ν-1). The reason for modelling (C-1), rather than C, as a Poisson random variable is to ensure that all symptoms have cause. The parameter ν is the average number of causes per symptom.

The waiting times from the symptom to the causes are exponential random variables. In Fig. 1(c) the causes are assumed rectangular and their size depends on duration and intensity. Therefore, the duration and intensity of each cause are modelled as exponential random variable distributions with

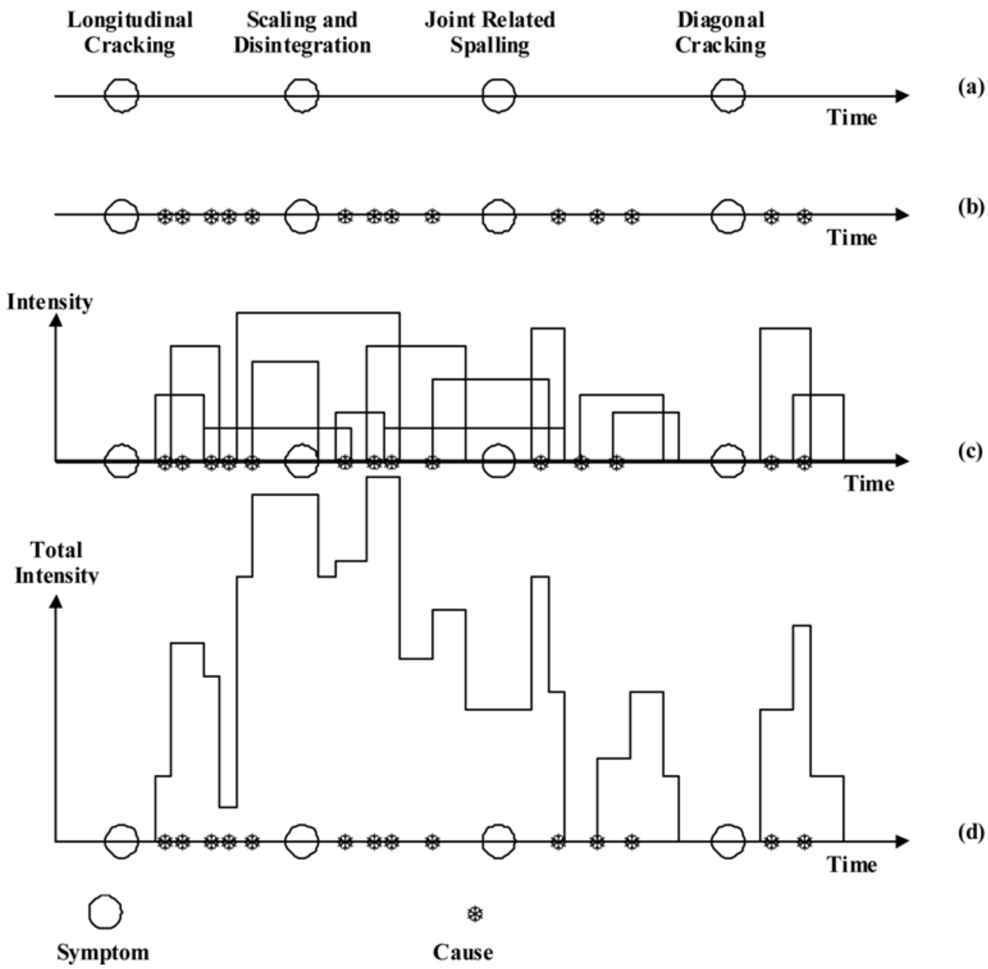

Fig. 1 A schematic representation of the concrete distress model

a mean of η hours and ξ per unit of time, respectively. The total intensity (Fig. 1(d)) at any point in time is the sum of the intensities of all active causes at that point and is calculated by a cumulative distribution function. The model is built up from Poisson processes and is defined by the four parameters λ, ν, η and ξ.

The parameters of the model should be estimated from past records and simulation of concrete distress needs random numbers from the Poisson distribution. In the case of the evaluation of concrete, because there are in most cases no past records available, the intensity of each symptom (or value of the random variable) should be estimated by defining a set of criteria such as width and depth of crack and surface appearance. The criteria and the probability of the value which influences concrete integrity and serviceability could be determined by visual inspection and engineering knowledge, judgement and experience.

5. Methodology and system architecture

The central feature of this research is the integration of two hitherto separate areas of Information Technology (IT). Firstly, integrated engineering computing systems have evolved and these are based upon sets of algorithmic programs that interact with a central database management system (DBMS) which works in collaboration with an evaluation management system (EMS). Secondly, knowledge-based programming techniques or expert systems (ES) are applied to a wide range of engineering problems. As expert systems are integrated into complex engineering computing environments, the database management capabilities of the integrated systems must be adapted to serve these new components.

The maintenance and repair of concrete structures represent a classical problem for the application of expert systems in collaboration with database management system (DBMS). The Diagnosis, Evaluation, Maintenance and Repair of Concrete structures – DEMAREC application (Moodi 2001) is developed as a new software which focuses on integration of concrete distresses (including cracking, surface and miscellaneous distresses), investigation and diagnosis problems, repair materials and methods and giving recommendations relating with them. DEMAREC is a Visual Basic interface (Fig. 2) in which a multiple production rules expert system (DEMAREC-EXPERT) is coupled to an independent database management system (REPCON) and an evaluation management program (ECON). A coupled independent subsystem connection between the DBMS, EMS and the expert system (ES) is considered for use in this research because of the need for flexibility and functionality in the interaction between the expert system, database, evaluation system and the user. The main implementation part of DEMAREC is characterised by an input and reporting system in the form of a visual edit screen, creating a database using Microsoft Access and

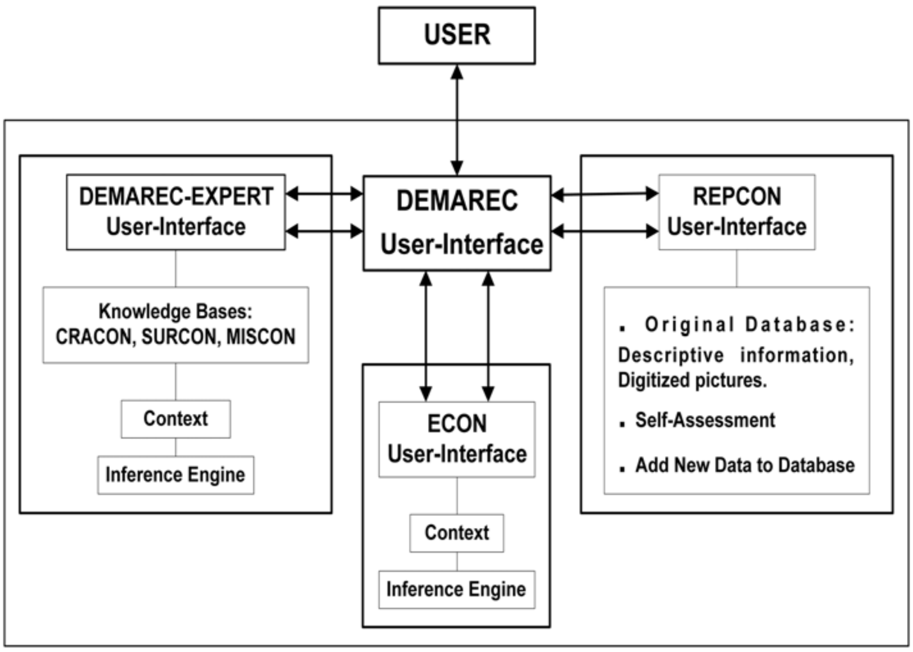

Fig. 2 DEMAREC architecture

the evaluation of uncertainty problems in concrete structures which embody Visual Basic programming. The main features of DEMAREC software include:

- Evolving knowledge and database.
- The integration of pictures and descriptive information in a way that makes problem solving easier.
- The creating of Graphical User Interface (GUI) gives inexperienced users the ability to access the full range of DEMAREC program capabilities in order to control the communication between the components of the program.
- An environment in which both experts and their added data can be evaluated and tested to ensure that the evolving system retains its integrity.

The new methodology of data/user evaluation and the modelling of the evolution within a field of expertise which is presented in DEMAREC (Moodi 2004) suggests that innovation with Information Technology (IT) can be applied to any areas of design and construction. The experience gained in implementing DEMAREC reveals several insights about the utility and integrity of the system. The respondents to this study who were experts at Newcastle upon Tyne University and selected organisations in the UK have suggested a number of tools that may emerge from future research. The important design and integration tools are on-line collaboration, simulation models, tools to capture client's requirements, communication and the Internet. One dominant research issue is improving the access of construction industry participants to information. The other dominant research theme is concerned with improving or visualising the design process.

The evaluation management interface for evaluation of concrete (ECON) is a Visual Basic interface shown in Fig. 3 which is structured with three different objects as cracking, scaling and

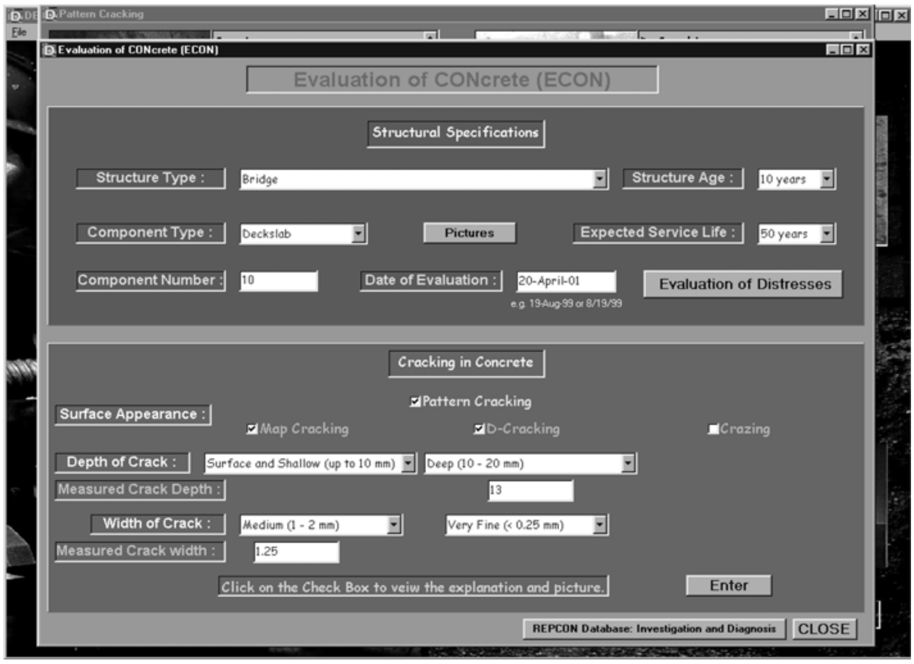

Fig. 3 The ECON user-interface

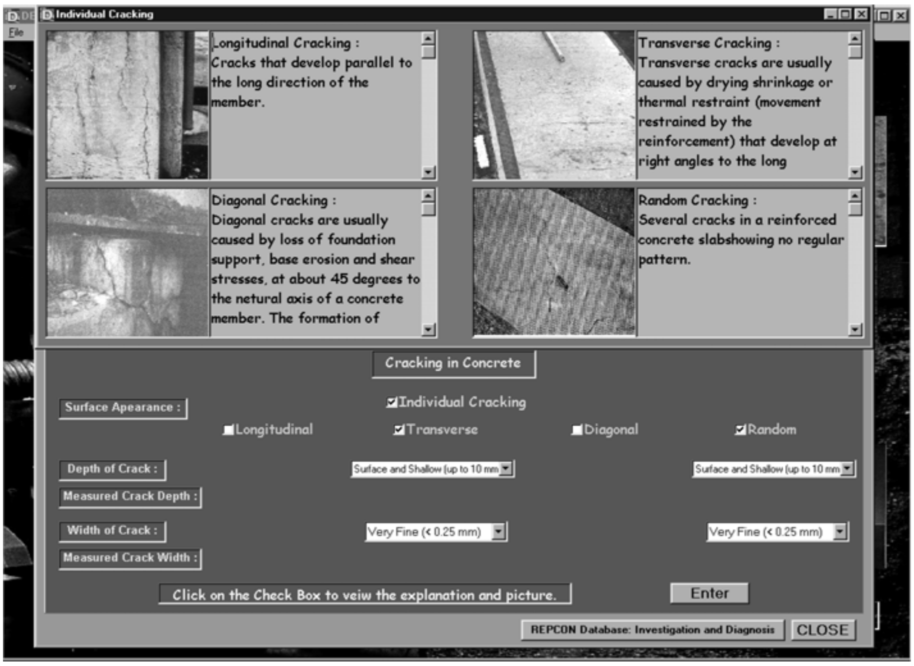

Fig. 4 Visual information used in ECON program

disintegration and spalling and delamination. The user can obtain assistance from the REPCON database (Knapton *et al.* 2000, Moodi 2001) of pictures alongside the descriptive information attached to each type of distress. Visual information (photographs and drawings) such as the one shown in Fig. 4 enhance the interpretation of results and can often describe failure modes for materials and structures.

The first step of any repair or rehabilitation work is a thorough and logical evaluation of the current state of the concrete in a structure, which should be begun by a visual inspection of the exposed concrete in an in-situ examination of the structure. The purpose of such an examination is to locate and define areas of distress or deterioration. A condition survey will usually include mapping of the various types of concrete deficiencies that might be found, such as; cracking, surface problems (disintegration and spalling) and joint deterioration.

It is important that the conditions observed be described in unambiguous terms that can be used in the evaluation of the current condition of the structure to be able to take engineering and management actions for the repair and maintenance of the structure. Terms typically used during a visual inspection are listed in Fig. 5. This information is included for determining the Deduct Values and for producing the confidence level (CL) in the ECON program for a good inspection, analysis and evaluation.

6. Assessing concrete distresses

One objective of an Evaluation Management System (EMS) 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. The criteria for the

Table 1 The Confidence Level (CL) for the Evaluation of Concrete (ECON) structure

Zone	Confidence Level (CL)	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 stabilisation. 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.	

evaluation of a concrete structure are shown in Table 1. This criteria is based on the considering management systems proposed by USACE (2000), FAA (2003), Cabrera *et al*. (1995) and Bullock *et al.* (1995), creating a more uniform method for evaluating and describing the overall structure conditions, creating a concise reporting system that indicates the deficiencies structure may have and the author's (Moodi 2001) experience and knowledge.

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 quantitative rating system for the condition of concrete in a structure would make possible the determination of which components within a structure most merit repair. The Evaluation Confidence Level (ECL) extends from 0 to 100, with 0 representing *Very Poor* condition and 100 representing *Excellent* condition. The Confidence Level (CL) is divided into *Minor*, *Moderate* and *Major* zones. In the minor zone (85-100), condition and function are generally at a level at which only periodic investigation and/or possible protection is needed. Structures falling in the moderate zone (50-70) show *Good* and *Fair* conditions for which the most potential for maintenance and repair alternatives typically exist. The conditions of *Poor* and *Very Poor* in major zone (0-30) are enough to warrant immediate attention and to recommend a safety evaluation.

The Confidence Level (CL) prescribed here applies to concrete structures in general. The rating system described allows the Confidence Level to be determined by visual inspection using limited equipment such as binocular, covermeter, ruler and carbonation depth. Values in each parts of the survey 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.

One of the main uses of Confidence Level (CL) values is to track changes in condition over time. With historical trends and knowledge of the structure environment, future rates of impairment may be estimated and used to plan the timing of repairs and corresponding maintenance expenditure.

7. Development of deduct values for various distresses in concrete structures

Confidence Level (CL) is developed by assigning specific Deduct Values to various types of distress in the concrete. These types of distress are defined in Fig. 2 by making a visual inspection of concrete in service. Primary Deduct Values are determined with the intent of obtaining a CL of 50 when the severity of an individual distress caused the safety of the structure to become questionable i.e., 50 is the critical value below which failure may occur. Deduct Values are subtracted from 100 to determine the Confidence Level (CL). The exact calculated Confidence Level from Deduct Values is determined by collecting subjective expert ratings based on the condition 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.

The Deduct Value is determined by visual inspection and by recording the information needed in the field inspection. The inspection and condition assessment procedure for determining Deduct Values is based on simple visual inspection techniques. If the condition of the structure being inspected is severely damaged i.e., a Confidence Level of below 50 more detailed investigation and engineering evaluation should be made.

The field inspection generates data for input to the PC-based REPCON Management System (Moodi *et al.* 2002) for evaluation of the current state of the structure. The REPCON Management System typically comprises modules such as preliminary inspection, inventory and review of existing documents to allow the user to take engineering and management decisions and to undertake a comprehensive investigation and condition survey. Review of existing documents such as construction or as-built drawings of the structure are necessary to determine such factors as physical dimensions and reinforcing details, which are needed for the inspection. Some of the required information is not used directly in producing Confidence Level (CL) values but is considered necessary for a good inspection, analysis, and evaluation.

8. Distress categories and deduct values

Deduct Values for various distress categories are classified in cracking in concrete, disintegration and scaling, spalling and delamination. An inspector should be familiar with the types of distress before performing an inspection to determine the Deduct Value. Deduct Values are based on considering previous works done and the author's (Moodi 2001) opinion and experience. They involve two considerations:

(1) The knowledge and experience of expert engineers in the safety of the structure which has been degraded by various types of distress, and

(2) Serviceability of the structure.

8.1 Cracking in concrete

A number of crack categories are provided including individual cracks such as longitudinal, transverse, diagonal and random, and such pattern cracking as crazing, D-cracking and map cracking. Deduct Values for crack categories are dependent on crack width and depth. By comparing ACI (ACI 2002 and ACI 2003), BSI (BSI 1997), RILEM (RILEM 1994) and European Committee for Standardization (EN 1504-3 2005) reports with U.S. Army Corps of Engineers (USACE 1995), 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 (Moodi 2001), the U.S. Army Corps of Engineers (USACE 1995) recommendations and the size of coarse aggregates (19-25 mm) used in the concrete.

Many other factors may contribute to or cause the impairment of concrete structures. These are described as structural distresses and are presented in the various forms of cracking and distresses such as flexural, shear, tensile, overloading and abnormal deflection cracking. Due to complexity of environment effects and their unknown combinations and availability of precise history of structural loading types in inspection, structural distresses are considered as multiplier coefficient into their following cracking deduct values in concrete.

8.2 Types of surface distress

Surface distress is categorized into disintegration, scaling, spalling and delamination. A number of concrete surface-loss modes is listed including scaling, dusting, honeycombing, wear and erosion, surface discolouration and scaling along cracking. A number of concrete volume-loss categories is also provided comprising spalling, popouts and pitting, joint related spalling and spalling caused by corrosion. Descriptions of surface appearance are provided by comparing ACI (ACI 2002 and ACI 2003), BSI (BSI 1997), RILEM (RILEM 1994) and European Committee for Standardization (EN 1504-3 2005) reports with the U.S. Army Corps of Engineers (USACE 1995) results. Deduct Values depend on estimated depth, extent and exposure of coarse aggregates.

9. Calculation of the Component Confidence Level (CCL)

Once the distress modes in each component of the structure to be rated are determined, the Component Confidence Level (CCL) can be calculated. By inputting the distress types into the ECON Management System software, hand calculation of Deduct Values and the Confidence Level (CL) can be avoided. By considering previous work done, generating a model for concrete distress simulation and the author's experience and knowledge, the following formula, which was recommended by Bullock *et al.* (1995) is used for calculating the Component Confidence Level (CCL). Selecting different weighting factors and using smaller percentage of each additional smaller deduct value is based on field test reports and comments (Bullock *et al.* 1995).

$$CCL = 100 - [1.0(DV_1) + 0.4(DV_2) + 0.2(DV_3) + 0.15(DV_4) + 0.1(DV_5)] \quad (1)$$

The Component Confidence Level (CCL) is based on the five largest deduct values (DV), with

Table 2 Example of calculation of the CCL for cracking to the external concrete paving at Unit A, Hams Hall

Step 1: Inspect component to determine distresses and quantities.

(64)
(24)

(61)
(54)

(23)
(51)

Step 2: Calculate Deduct Values for each distress.

(64) JSP-SL = 5 (61) SP-MO = 20 (23) PMC-DE-ME = 30
(24) ILC-DE-WI = 40 (54) WEA-SL = 5 (51) SC-VSL = 5

Step 3: Rank the Deduct Values in descending order to the smallest. Only the five largest are used in the Component Confidence Level (CCL) calculation.

	Distress and Quantity (Step 1)	Deduct Value (Step 2)	Rank (Step 3)
1-	(64) JSP-SL	5	DV_4
2-	(24) ILC-DE-WI	40	DV_1
3-	(61) SP-MO	20	DV_3
4-	(54) WEA-SL	5	DV_5
5-	(23) PMC-DE-ME	30	DV_2
6-	(51) SC-VSL	5	-

Step 4: Calculate the CCL based on the ranked Deduct Values:

$$CCL = 100 - [1.0(DV_1) + 0.4(DV_2) + 0.2(DV_3) + 0.15(DV_4) + 0.1(DV_5)]$$

$$CCL = 100 - [1.0(40) + 0.4(30) + 0.2(40) + 0.15(5) + 0.1(5)] = 42.75$$

The CCL is 42-75 which is Poor according to Table 1 (Severe impairments in at least some major components of the structure have been occurred)

ILC= Individual Longitudinal Cracking DE= Deep WI= Wide ME= Medium
PMC= Pattern Cracking SP= Spalling SC= Scaling VSL= Very Slightly
SL=Slightly MO=Moderate WEA= Abrasion JSP= Joint Related Spalling

DV_1 the largest value and other values in descending order to the fifth largest, DV_5. Table 4 shows an example of how the Component Confidence Level (CCL) for a column has been calculated.

To determine a component confidence level (CCL) by ECON program, the type of information and observations needed to be entered such as the one shown in Fig. 4 and finally the calculation confidence level for each component is done. Fig. 6 illustrates the CCL for a bridge deck slab. After identifying the Deduct Value for each distress of a component and determining the confidence level for each component of a structure, the confidence level of structural components is included in a format such as the one shown in Fig. 7.

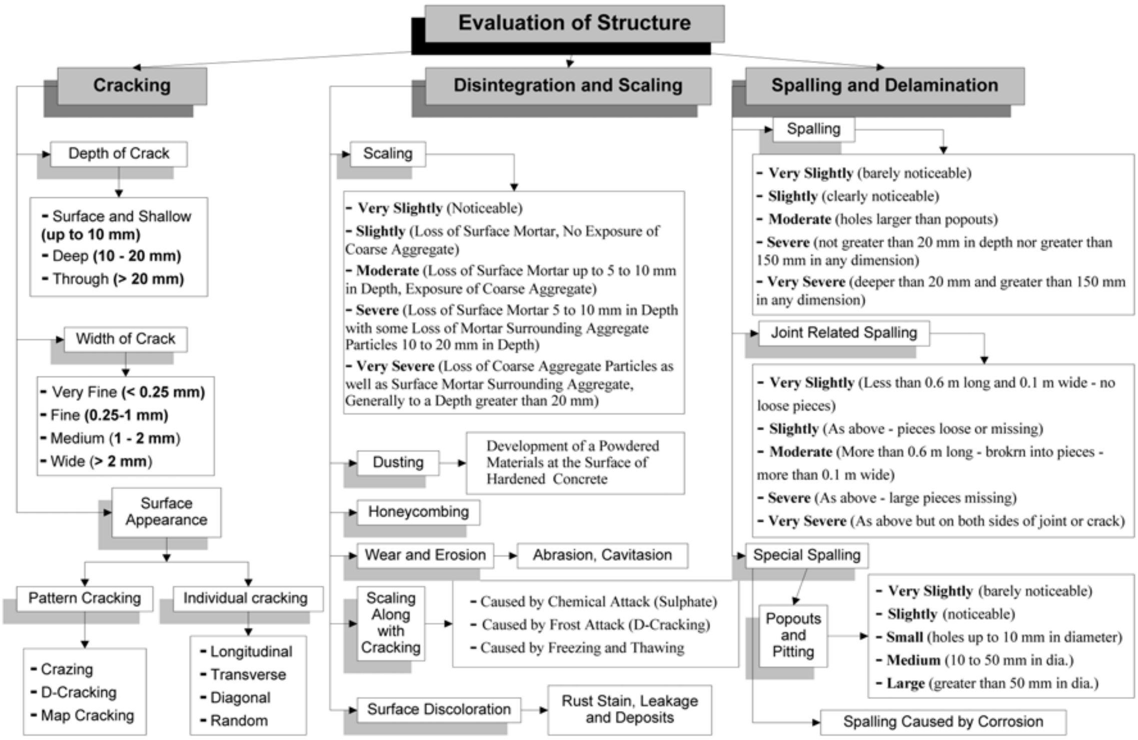

Fig. 5 Distress categories used in a visual inspection

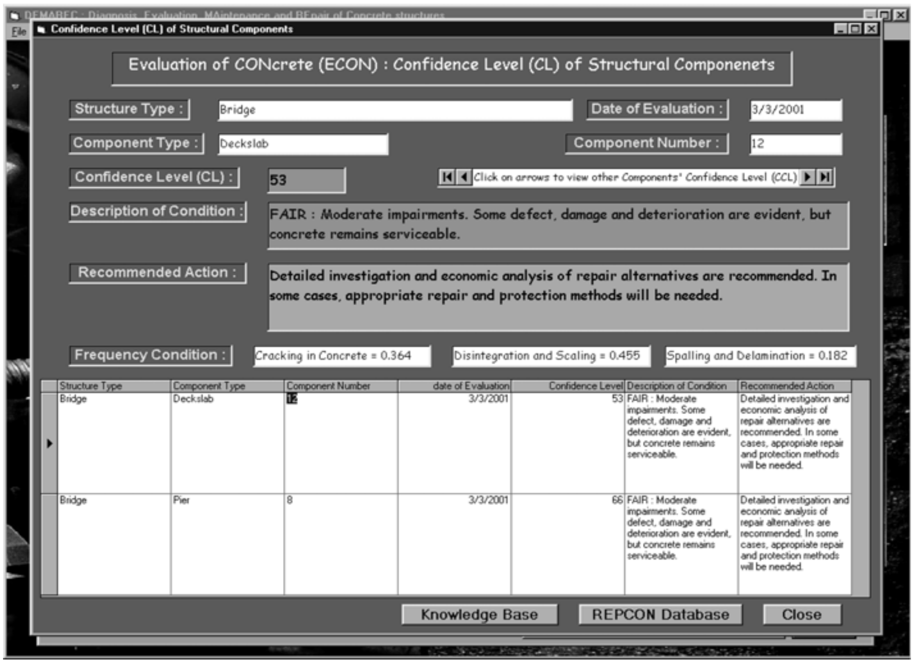

Fig. 6 A screen dump of calculation of the CCL for a bridge deck slab by ECON program

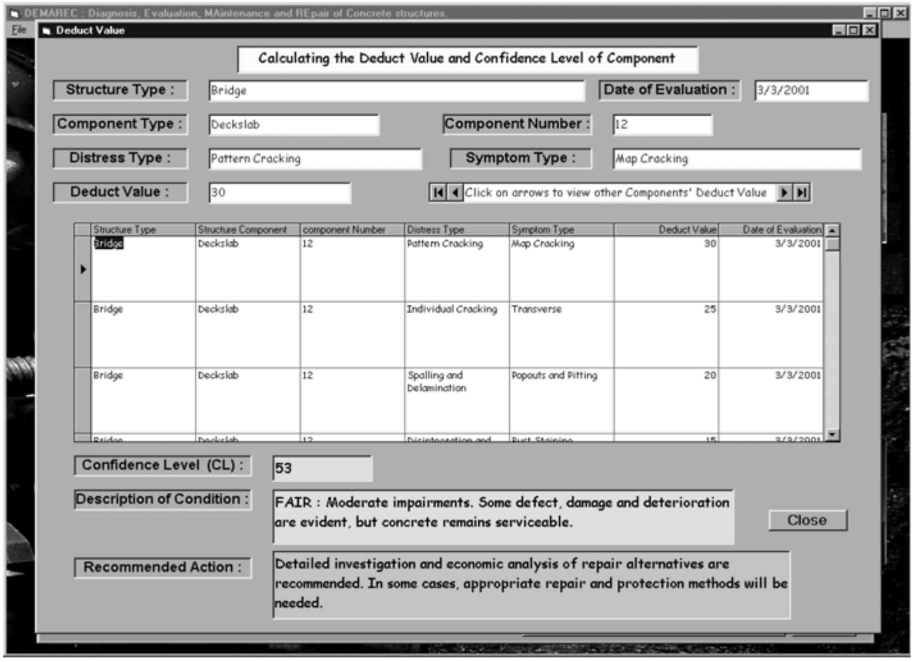

Fig. 7 A screen dump of confidence level of structural components

10. Validation and case study

The principal value of DEMAREC is as a platform for the long-term development of an integrated engineering computing environment. The conceptual architecture for the environment consists of multiple knowledge base tools, user interfaces, evaluation program and databases supported on networked processors to form a simple integrated system. Certainly the research has succeeded in addressing many of the issues in the coupling of evaluation systems with database management systems for concrete repair applications. The original focus of research on developing a flexible interface system has been substantially achieved. In the prototype implementation, evaluation systems may pose arbitrary queries in the context of their own data structures which are then answered using data from the database that is hidden from evaluation system (ES). As a database interface for an evaluation system, a major strength of ECON has proved to be its provisions for handling dynamically added data. In addition, ECON deals with engineering data and the needs of engineering applications with respect to that data in the field of concrete repair. Considerations were given to the design process for ECON. The global schema uses a data model to provide maximum semantic representation capabilities. This is illustrated by comparing pictures and technical data in a way that makes decision and problem solving easier. Finally, the ECON results are validated by some case studies taken from actual cases of concrete diagnosis and repair, i.e.

(1) Cracking to the external concrete paving, at Unit A, Hams Hall (Knapton 2001) being used by Tradeteam as a consumer-products distribution centre is considered. The cracks are full depth and move with moisture and temperature variation. Spalling and general deterioration in the slab and near openings and joints is occurring. From the pattern cracking, and from the other test reports, it is clear that there is insufficient release of restraint at the joints for the slabs to operate by the joints

Table 3 Comparison of results between DEMAREC application and external paving investigation

	Possible causes or considered	Alternative materials	Alternative methods
DEMAREC-EXPERT system	* Dowel bar misalignment * Late sawing of joint * Thermal expansion * Shrinkage * Temperature changes * Curling * Poor load transfer * Loss of substrate	* Fibre Reinforced Polymer (FRP) * Expansion cements (Types K, M, S)	Concrete replacement * Fibre-reinforced concrete * Shrinkage compensating concrete
External paving investigation	* Temperature & moisture changes Led to shrinkage and curling * Dowel bar misalignment * Poor load transfer * Differential settlement	* Air entrainment * Polypropylene fibre	Concrete replacement

moving and thereby accommodating temperature/moisture induced volume changes. A secondary contribution to the development of the cracking has resulted from dowel bar misalignment. It was recommended that the slabs should be replaced with unreinforced concrete and that either air entrainment or polypropylene fibres should be included in the concrete.

In order to assess the validity of the DEMAREC system results in assessing the reasons for the pattern of cracking in the Tradeteam external pavement, the following conclusion can be reached. Firstly, causes and effects of cracking obtained from the DEMAREC-EXPERT conclusion could help the user in correctly diagnosing the distresses. Secondly, the component confidence level (CCL) for the external concrete pavement is calculated by ECON program (Table 2). Finally, alternative repair materials and methods alongside the durability recommendation extracted from the REPCON database allow the user to select the best course of repair and maintenance. The comparison of results is also shown in Table 3.

(2) Some of the concrete structures in industrial situations are subjected to various distresses due to different activities and lack of timely attention. These impairments cause incompatibility changes on mechanical, physical and chemical concrete properties and usually along with concrete disintegration. Unfortunately, lack of timely attention and determination of concrete distress causes, especially in places where periodic inspections have not been implemented at regular intervals, often cause concrete structures to become degraded and the estimation of these damages have shown a high cost of repair activities. Therefore, in order to achieve an adequate evaluation and actual cause of impairment and to provide the inspection, maintenance and repair strategies along with acceptable criteria in concrete structures, a management framework for periodic assessment of concrete structures in the Mobarekeh Steel Complex base on ECON program is provided (Moodi *et al.* 2009).

With respect to evaluation of current concrete structures application and according to objectives of ECON program, deteriorations are classified in five groups as shown in Fig. 8. The purpose of this evaluation is to gather information about distresses severity and extent. This information is only obtained from a thorough and logical inspection and completed inspection forms for concrete structures. In addition, for planning maintenance of structure during its service life, periodic and regular inspections and preventing from distress progress and development which are important for

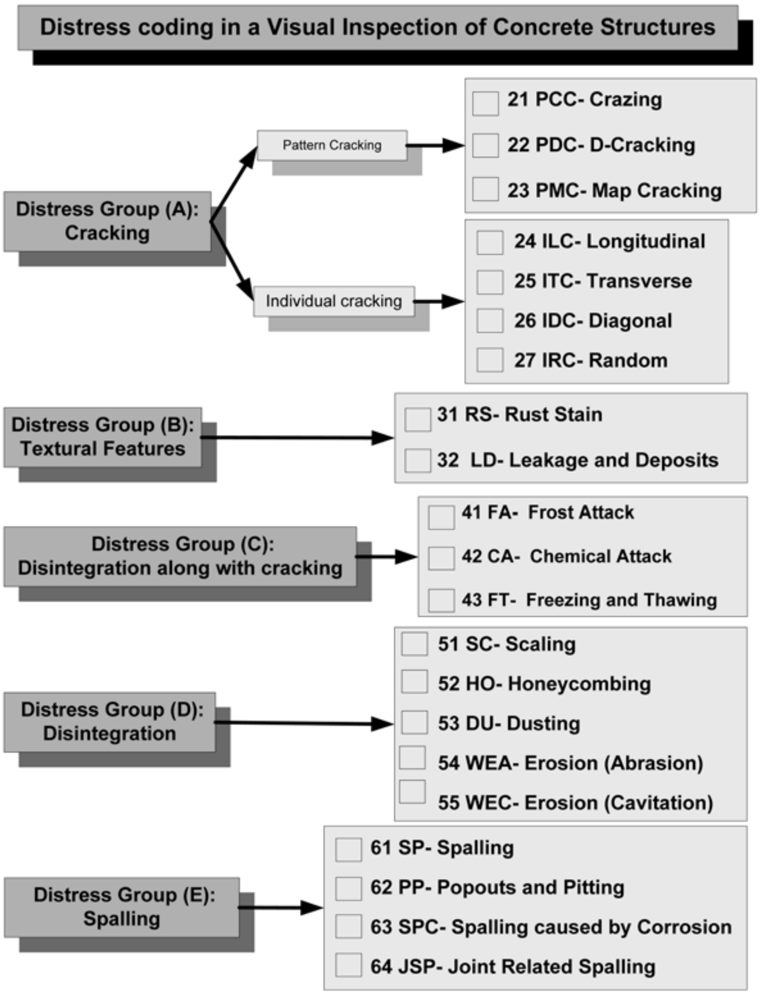

Fig. 8 Distress coding in a visual inspection in a concrete structure based on ECON program

enhancing service life of concrete structures, different inspection forms are provided (Fig. 9).

(3) Investigation of concrete distresses in cooling tower unit 28 (Moodi *et al.* 2009) which is one of the concrete structures in the Mobarekeh Steel Complex in central of Iran. This structure is used for cooling and decreasing water temperature circulated in the steel production lines. The concrete was subjected to circulation of industrial water and under aggressive sulfates, corrosion of reinforcement, without periodical inspections at regular time intervals and thus serious deteriorations were presented. Damages owing to corrosion of reinforcement have caused expansion and eventually resulted in cracking, delaminating and spalling of concrete.

By using ECON program the components confidence level (CCL) of the cooling tower was calculated (Table 4). The recommended action by ECON was detailed investigation and an engineering evaluation should be made to determine the demand for repair. In order to have an optimal use of the structure and its stability and achieving an adequate repair procedure, a thorough and logical investigation of distress causes was carried out. The survey includes information collection and

Inspection and Monitoring of Concrete Structures
Mobarekeh Steel Complex
Component Confidence Level (CCL) calculation

Concrete Technology and Durability Research Centre
Amirkabir University of Technology

Building Name: Last Inspection Date: Inspector Name:

Element Position: Structural Element Type:

Distress Groups and Coding **Deduct Values**

Distress Group (A): Cracking		VFI	FI	ME	WI
21 PCC - Crazing	SS	5	10	-	-
22 PDC - D-Cracking	SS	5	10	-	-
	DE	10	20	30	40
	TH	15	30	40	50
23 PMC - Map Cracking	SS	5	10	20	30
	DE	10	20	30	40
	TH	15	30	40	50
24 ILC - Longitudinal	SS	5	10	20	30
	DE	10	20	30	40
	TH	20	30	50	70
25 ITC - Transverse	SS	2	5	10	15
	DE	5	10	15	30
	TH	10	15	25	40
26 IDC - Diagonal	SS	10	20	30	40
	DE	15	30	40	60
	TH	20	40	60	80
27 IRC - Random	SS	5	10	20	30
	DE	10	20	30	40
	TH	15	25	40	60

Distress Group (B): Textural Features	VSL	SL	MO	SE	VSE
31 RS - Rust Stain	-	10	-	15	-
32 LD - Leakage and Deposits	2	5	10	15	20

Distress Group (C): Disintegration along with Cracking	VSL	SL	MO	SE	VSE
41 FA - Frost Attack	-	5	10	30	-
42 CA - Chemical Attack	5	15	25	40	60
43 FT - Freezing and Thawing	5	15	25	40	60

Distress Group (D): Disintegration	VSL	SL	MO	SE	VSE
51 SC - Scaling	5	10	20	30	50
52 HO - Honeycombing	2	5	10	20	30
53 DU - Dusting	-	5	-	10	-
54 WEA - Erosion (Abrasion)	2	5	10	20	30
55 WEC - Erosion (Cavitation)	5	10	20	40	60

Distress Group (E): Spalling	VSL	SL	MO	SE	VSE
61 SP - Spalling	5	10	20	30	50
62 PP - Popouts and Pitting	2	5	10	20	30
63 SPC - Spalling Caused by Corrosion	-	30	-	60	-
64 JSP - Joint Related Spalling	2	5	10	20	30

SS: Surface and Shallow
DE: Deep
TH: Through

VFI: Very Fine
FI: Fine
ME: Medium
WI: Wide

VSL: Very Slightly
SL: Slightly
MO: Moderate
SE: Severe
VSE: Very Severe

Deduct Values in Descending Order	
DV1	
DV2	
DV3	
DV4	
DV5	
DV6	
DV7	

Component Confidence Level calculation

$$CCL = 100 - [1.0(DV_1) + 0.4(DV_2) + 0.2(DV_3) + 0.15(DV_4) + 0.1(DV_5)]$$

CCL =

Description of Element Condition according to Table 1 Ceriteria

Form: ASS-DV-CCL-EL-G

Fig. 9 Component confidence level calculation form

visual surveying and sketching of distress locations, several in-situ NDT tests, determination of various aggressive ions in the depth of concrete, and some other laboratory tests on core specimens taken from selected components of the structure. Finally, based on the results of preliminary inspections and in-situ and laboratory tests and using the DEMAREC system, various deterioration mechanisms were determined and then concrete removal methods and adequate repair procedures

Table 4 Example of calculation of the CCL for a column of cooling tower unit 28 in Mobarekeh steel complex

Step 1: Inspect component to determine distresses and quantities.

(24) (51) (32) — (43) — (24) (42)

Step 2: Calculate Deduct Values for each distress.

(24) ILC-TH-WI = 70   (43) FT-SE = 40   (24) ILC-DE-ME = 30

(51) SC-SL = 10   (42) CA-SE = 40

(32) LD-SL = 5

Step 3: Rank the Deduct Values in descending order to the smallest. Only the five largest are used in the Component Confidence Level (CCL) calculation.

Distress and Quantity (Step 1)	Deduct Value (Step 2)	Rank (Step 3)
1. (24) ILC-TH-WI	70	DV_1
2. (42) CA-SE	40	DV_3
3. (43) FT-SE	40	DV_2
4. (24) ILC-DE-ME	30	DV_4
5. (51) SC-SL	10	DV_5
6. (32) LD-SL	5	-

Step 4: Calculate the CCL based on the ranked Deduct Values:

$$CCL = 100 - [1.0(DV_1) + 0.4(DV_2) + 0.2(DV_3) + 0.15(DV_4) + 0.1(DV_5)]$$

$$CCL = 100 - [1.0(70) + 0.4(40) + 0.2(40) + 0.15(30) + 0.1(10)] = 0.50$$

The CCL is 0.5 which is Very Poor according to Table 1 (Very severe and extensive impairments in most columns of the structure)

ILC- Individual Longitudinal Cracking   TH- Through   WI- Wide   DE- Deep
CA- Chemical Attack   SE- Severe   FT- Freezing and Thawing   ME- Medium
SC- Scaling   LD- Leakage and Deposits   SL- Slightly

were suggested.

In these case studies, it is shown that the results of this research could have been used to enhance the process of determining the cause of failure and in selecting the repair material and method. Engineering judgement and experience alongside the site investigation and in-situ and laboratory examinations were able to confirm the final conclusion.

11. Conclusions

One objective of an evaluation management system is to create assessment procedures that will allow the current condition of the structure and its components to be expressed numerically so as to assist in choosing the best course of action in the repair and maintenance management. Engineering judgement and experience were needed to develop a set of criteria in order to implement a quantitative rating of the overall state of concrete using the results of the observation of signs of distress and weighting scales based on severity and extent. It is important that the conditions observed be described in unambiguous terms that can be used by the user to be able to take engineering and management actions for the repair and maintenance of the structure.

One of the innovations in this application is the use of pictures from the REPair of CONcrete (REPCON) database as a basis for the diagnosis of distress in concrete structures alongside the descriptive information attached to each type of distress. Visual information (photographs and drawings) enhance the interpretation of results and can often describe failure modes for materials and structures. This is expected to solve the problem of inconsistency of terminology in describing modes of distress. This enables even the inexperienced user to diagnose a damaged concrete component by comparing the distress of the concrete against the pictures in the database.

More effort has to be placed into supporting the exchange of information and knowledge between the various experts whilst allowing them to work on their respective parts of the knowledge and experience. Effectively, the benefit of using ECON lies in the enhanced levels of confidence which can be attributed to the data and to contributors of that data so that the expertise moves on in a faster and more structured manner.

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