An expert system for diagnosing fire-caused damages to reinforced-concrete tunnel lining

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Abstract: During the last four decades, reinforced-concrete structure failures have been happening widely for many reasons, such as increased service loads, fire, and durability problems. The economic losses due to those failures are very high. An expert system is an interactive computer-based decision tool that uses both facts and heuristics to solve difficult problems based on knowledge acquired from experts. To realize these requirements, a logic programming visual basic language is used together with visual diagnosis. The expert system, Diagnosis of Fire-Caused Damages to Reinforced-Concrete Tunnel Lining (DFCDRCTL) was developed in this work for diagnosing the annual damages caused by fire. The program is used as an alternative of a human expert to make annual technical decisions in diagnosing fire damages at the second reinforced-concrete tunnel lining segment. It is concluded that the proposed DFCDRCTL expert system is easy to use, and is fast and helpful for engineers.

Keywords: expert system; fire damage of reinforced concrete; tunnel lining damage

1 Introduction

Fires in road tunnels endanger people and often cause considerable damage to facilities. Several serious accidents that took place in recent years have led to an increasing public interest in tunnel safety and efforts by the highway authorities to make tunnels safe. In the recent researches and developments in science and technology, many attempts have been always made to overcome the problems of people. The advancements made in the fields of artificial intelligence, computer science and engineering have tackled the problems related to mental and intellectual processes of the people. These programs ask a series of questions about the concerned problem and give appropriate advice based on its pool of knowledge. The knowledge used by the expert system includes either rules or experienced information about the behaviors of tunnel lining segment under fire. Such systems can be designed for specific hardware and software configurations, or they can be software systems that are designed to run on a general-purpose computer. The main objective of this study was to classify damage in reinforced-concrete tunnel lining, also called second lining, according to available literature and expert opinions.

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2 Expert systems (ES)

The ES is an application of artificial intelligence (AI), and which first emerged in mid-1960s. The basic idea behind ES is simply the expertise, which is the vast body of task-specific knowledge and transferred from a human brain to computer software. This knowledge is then stored and used for specific advice as needed [1].

The tunnel expert system compiles expert knowledge and tools for facilitating data collection and processing, data analysis and evaluation, and decision making in tunnel construction. The working processes contain 3 major blocks, i.e., 1) construction data collection at the site, 2) tool bank for various data processing, analysis, simulation and evaluation, and 3) decision making for support design and construction procedures recommendation, safety evaluation and construction status demonstration [2].

Empirical tunnel safety criterion based on case histories in Taiwan is used in the safety evaluation of tunnels. Regarding the criteria, the information of the tunnel inward movement (δ), tunnel radius (R), rock mass strength (UCS) and actual performance of tunnel case histories were used to establish 3 warning levels of tunnel safety and the necessary measures to be taken to develop export system for tunnel safety [3].

Farinha et al. [4] established systems for diagnosis and repair of old railway tunnels. The results obtained by the application of that system have proved the importance of using support methodologies based on many techniques in safety control of railway tunnels.

Yu and Chern [5] improved the system for drill and blast tunnel construction in Taiwan by using expert system technology. The system provides multi-expertise assistance to the decision of support system and to the procedures of excavation at the construction site. Also the system provides rationale estimation of the tunnel deformation under selected support system and construction procedure with the aid of an artificial neural network approach.

3 Fire damage of reinforcement concrete

When reinforced concrete is subjected to high temperature as in fire, there will be deterioration in its properties. The loss in compressive strength, cracking and spalling of concrete, destruction of the bond among the cement paste and the aggregates and the gradual deterioration of the hardened cement paste observed are of high importance. Assessment of fire-damaged concrete usually starts with visual observation of color change, cracking and spalling of the surface. The color of concrete provides a broad, general guide of temperatures, and whether the color represents the original surface or resulting from spalling. Crazing, cracks caused by quartz or chart aggregate particles, spalling and dehydration (crumbling and powdering of paste) are general indications of temperatures to which concrete has been exposed as shown in Fig. 1. On heating above 300 °C the color of concrete can change from normal to pink (300 °C to 600 °C) to whitish gray (600 °C to 900 °C) and buff (900 °C to 1 000 °C). The pink discoloration results from the presence of iron compound in the fine or coarse aggregates [6].

Fig. 2 demonstrates the structural loss in strength of concrete and reinforcement steel.

![Concrete color and temperature](image)

**Concrete color**

<table>
<thead>
<tr>
<th>Color</th>
<th>Temperature</th>
<th>Other possible physical effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buff</td>
<td>950 °C</td>
<td>Powdered, light colored, dehydrated paste</td>
</tr>
<tr>
<td>Black</td>
<td>900 °C</td>
<td>Spalling, exposing not more than 25% of reinforcing bar surface</td>
</tr>
<tr>
<td>Gray through buff</td>
<td>800 °C</td>
<td>Popouts over chert or quartz aggregate particles</td>
</tr>
<tr>
<td>Pink to red</td>
<td>600 °C</td>
<td>Deep cracking</td>
</tr>
<tr>
<td>Normal</td>
<td>300 °C</td>
<td>Surface crazing</td>
</tr>
<tr>
<td>40 °C</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1 Visual evidence of temperature to which concrete has been heated.

![Effects of temperature on concrete and steel reinforcement](image)

Fig. 2 Effects of temperature on concrete and steel reinforcement: Concrete and steel start to lose strength at temperature between 250 °C to 300 °C, lose 50% strength at 550 °C.
4 Problem identification

In General, there are three results for diagnosis:
1) Simple damage, which is based on the following criteria:
   • Spalling not found at deflection or underside of arch at the reinforced concrete tunnel lining;
   • The color of reinforced concrete tunnel lining being normal;
   • The cracks of hairline type; and
   • The strength without any reduction.
   Hint: The fire temperature is less than 250 °C and fire time resistance less than the fire resistance rate.
2) Moderate damage, which achieved by the following criteria:
   • Spalling found.
   • The color of tunnel lining being brown to pinkish;
   • The cracks width close to 0.13 mm.
   • Small reduction in strength.
   Hint: The temperature is between 300 °C to 500 °C.
3) Severe damage, which achieved by the following criteria:
   • Spalling found;
   • The color of structural element being grey to buff;
   • The width of crack more than 0.35 mm; and
   • More reduction in strength.
   Hint: The temperature is more than 700 °C.

5 Investigation of reinforced concrete tunnel lining deterioration

5.1 Stage approach

Any investigation can conveniently be split into two stages as follows:
Stage 1. An initial survey to identify the cause of the problems.
Stage 2. An extension of the Stage 1 survey, perhaps using a limited number of techniques to identify the extent of the defects revealed by Stage 1.

5.2 Visual survey

After collecting background data, testing should begin with visual survey of the structure. This may conveniently be recorded on a developed elevation giving particular attention to the following defects:
• Cracks or crazing;
• Spalling;
• Hollow surfaces;
• Varying color or texture;
• External contamination or surface deposits.

6 Domain knowledge.

It is difficult for novice application user to select an appropriate model directly. Comparatively, simple interactive questionnaires, incorporating most of questions related to users’ knowledge, are easy to understand and response. Good questionnaires can infer the intrinsic conditions of model selection on the basis of responses from the users. The domain knowledge entailed in the development of the prototype system has been encoded mainly on the basis of literature review and interview with experienced numerical modelers.

Project types usually impose some limitations on the application of certain models. If reservoir routing is considered as an example, the analysis can be simplified significantly since dynamic effects are neglected and only the continuity equation needs to be considered. A finite-difference approximation can be utilized to describe the change of storages, i.e., the classic continuity equation of deSaint-Venant [8].

Visual window tabular interfaces are designed here, on the basis of experience and knowledge of the domain experts. Each tab helps the user to locate different groups of questionnaire. Fig. 3 shows the main menu of the system. There are three choices (circular, rectangular and exit). The selection from one of them is according to the type of tunnel that has a damage or exit from the system. For example, selecting horseshoe tunnel gives an interface as shown in Fig. 4. Fig. 4 shows that there are four choices also (Cracking, Spalling, Deflection, or Back to Main Menu). The program will proceed according to the question that guides the user for final decision.

![Fig. 3 The main menu of the program.](image-url)
7 Knowledge base

7.1 Production rules

In this study, rules are used because they are the most common forms of statement in representing the knowledge. Each rule consists of one or more conditions, which, if satisfied, gives rise to one or more actions. A rule can be expressed with the following general form

\[
\text{IF (condition) THEN (conclusion or action)}
\]

Such rules are sometimes called production rules because they produce a result. For example: IF the type of damages in the tunnel lining is cracking AND the cracks appear on all the sides AND the cracks are longitudinal AND the cracks follow the pattern of the reinforcement THEN CAUSES. This flowchart starts with the main menu that includes the main types of tunnel lining to be identified. For every type of these damages there are several choices and questions from which the type of the damage is specified. This method begins from the conditions or events until reaching goals.

7.2 Inference engine

Provided that the logical structures of the application problem have been carefully designed, all anticipative conclusions can be generated automatically by robust inference engines that control the strategies determining how, from where, and in what order knowledge base draws its conclusions. These inferences strategies mimic the reasoning processes in solving a real problem by a domain expert.

The analysis of the acquired knowledge is done continually together with acquisition process. The process of the diagnosis of the damages is applied as a menu-driven with questions ‘n’ answers; the process comprises all steps as abstracted in the data flow diagram that has been shown in Fig. 5.
Fig. 5 Flow chart describing the DFCDRCTL mechanism (to be continued)
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8 Case study

The Mont-Blanc Tunnel overview\textsuperscript{[10]} is as follows.

Location: Between Courmayeur, Italy and Chamonix, France

Fire event: On 24 March 1999, a truck fire at 6.7 km into the Italian part, spreading to 35 other vehicles, fire duration of 53 h.

Fire damage: Extensive tunnel roof and road pavement damage

Fire resistance: No fire protection

Function: Road tunnel

Dimensions: Width of 8.6 m; length of 11.6 km

Tunnel established in: 1965

Figs. 6 and 7 show the plane and the damages at the Mont-Blanc tunnel.

Fig. 5 Flow chart describing DFCDRCTL mechanism

Fig. 6 Mont-Blanc Tunnel plane
9 Results of the system

The user interacts with the system through a user interface that simplifies communication and hides much of the complexity, such as the internal structure of the rule base. Expert system interfaces employ a variety of user styles, including question-and-answer, menu-driven, or graphic interfaces. The final decision on the interface is a compromise type among user’s needs and the requirements of the knowledge base and inference system. The heart of the expert system is the knowledge base, which contains the knowledge of a particular application domain. In a rule-based expert system this knowledge is presented as “if... then...” rules. The knowledge base contains general knowledge as well as case-specific information.

The knowledge of the DFCDRCTL expert system is represented as a tree of rules including all questions that users may be required to answer to lead towards the solution. The constructed tree is the space of problem of the DFCDRCTL expert system. The inference engine applies the knowledge to the solution of actual problems.

In the production system, the inference engine performs the recognize-act control cycle. The procedures that implement the control cycle were separated from the production rules themselves. In this DFCDRCTL expert system considered the Expert System as Lifecycle. The procedure of the execution is beginning with menu-driven to select the type of the simple R.C tunnel lining such as rectangular, circulars tunnel. After this step there are a sub-menu used to select the type of the crack damage occur in the simple R.C tunnel lining segment. The next step represents the scenario and dialog between the DFCDRCTL expert system and the user. The scenario is done by the question-and-answer, where the expert system asks and the user answer until reaching to the goal of the diagnosis.

10 Conclusions

From the present theoretical study and based on its results, the following points are concluded.

1) The expert system DFCDRCTL developed in this work is a diagnostic advisory system that can be used as an alternative to the human expert, to give technical decisions in diagnosing fire damages in reinforced concrete tunnel lining segment.

2) The most difficult stage of expert system development is the knowledge acquisition because the effectiveness, efficiency and reliability of the developed system highly depend on the quality and quantity of its knowledge base.

3) The decision on the type of fire damage made by the system, is a multitask process which requires the user to provide necessary information about the conditions of the tunnel lining gathered by both visual and technical tests.

4) The using of the DFCDRCTL expert system is easy, fast and give successful answer for engineers, because it takes most all perhaps damages into consideration.

5) The development of the DFCDRCTL expert system may be done by updating the knowledge base in the system without changing the inference engine.

6) The DFCDRCTL expert system can be used to include the interaction between the system results.

7) The program recommended can give suitable diagnoses for damage.

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