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Integrating neural networks, databases and numerical software for managing early age concrete crack prediction

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ABSTRACT: *This paper presents an expert system that supports early age concrete crack prediction. The system embodies knowledge gathered from experts both in procedural form (programs and spreadsheets) and declarative form (graphical assistants, users' guides, documentation). Moreover, processing tasks are performed by neural networks trained on data gathered from experimental and virtual models. The system comprises a large database for storing data about concrete mixes. The procedures of the expert system can access the database and exploit its data for processing purposes.*

1 INTRODUCTION

This paper presents the achievements of a task of the IPACS project, a research granted by the European Communities to evaluate, integrate and extend the existing knowledge about early age concrete crack prediction in engineering practice.

The task was devoted to the design and development of software tools useful for contractors and designers for managing early crack prediction (Dalmagioni et al. 2002). These tools consist of a knowledge based system simulating basic early age transient concrete properties, and data bases for storing the same properties, standardized laboratory and field tests, and recommendations and specifications (Salvaneschi & Lazzari 1997). They have been collected and organized into an expert system (called IPACS) able to:

- support the evaluation of the cracking risk in concrete structures;
- indicate possible actions for optimization of technical quality and economy.

The system is focused on assisting the engineer in the decision-making process, offering guidance in assessing critical conditions leading to cracking. It is an integrated and easy to use tool hosting various pieces of codes, databases and logical rules taken by experts in this field, which cannot be all represented by formal mathematical algorithms.

The software may simulate the concrete hardening and building processes taking into account all important factors of influence, such as climatic conditions, non-uniform maturity development, restraints imposed by adjoining structures etc.

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Some of the reasoning agents within the system have been developed through neural networks, which were trained on data gathered from experiments, site observations, mathematical modeling coming from other tasks of the IPACS project.

2 EXPERT SYSTEMS & CIVIL ENGINEERING

Artificial intelligence (A.I.) technology was presented to the international structural community in the early 1980s and experienced an enormous growth of applications in the latter part of the same decade.

From the broad spectrum of the A.I. sub-fields, civil engineering applications belong essentially to the so-called expert systems, also known as knowledge-based systems.

They are software systems that include a corpus of expert knowledge and processing abilities to deal with data in a way that can be compared with that of experts of the domain.

Therefore, their development and success is strictly related to the availability of theoretical and practical experience on the application field, and to its formalization toward its embodiment into a software system - this process emerges from a joint effort of field experts and A.I. people to identify and correctly exploit the knowledge necessary for solving the problem to be faced by the expert system.

From the point of view of the applications, they belong to two main threads:

1. design;
2. diagnosis.

Generally, those interested in the applications to design, that is support systems which help designers in (part) of their tasks, do not deal with decision support in the field of structural assessment, and vice versa.

An intriguing aspect of the IPACS project is that the expert system to be develop had to be concerned both with supporting design of new concrete mixes and with diagnosis of existing mixes.

With reference to the concrete industry, the number of real application of A.I. technologies is still not large. Some of them deal with the support of site personnel when they choose the type of fresh concrete (BETVAL, Technical Research Center, Finland; COMIX, Central Laboratories, New Zealand); some others support the diagnosis and the definition of repair strategies of deteriorated concrete structures and pavements (ContecES, Darmstadt University of Technology, Germany; EXPEAR, Federal Highway Administration, U.S.A.; PAVE, French National Research Council, France).

The National Institute of Standards and Technology of the U.S. Bureau of Reclamation has also undertaken the development of several interesting A.I. based tools and databases to face several problems related to high-performance concrete production and management, and to develop and implement computational and experimental materials science-based techniques in order to enable the prediction and optimization of the initial cost and service life performance and minimize the environmental impact of concrete in the built infrastructure. They have also used cellular automata to model microstructural development of cement paste during hydration.

Eventually, the group of Knowledge-based systems of the Civil Engineering Department of the University of the Arabic Emirates has developed a system to support the production of concrete for hot weather conditions, that is the other side of the problem to be dealt by IPACS partners, who mainly come from northern Europe, were low temperatures affect concrete hardening.

3 THE SOFTWARE ARCHITECTURE

IPACS has been developed exploiting the Internet technology, so that users may easily share knowledge and data via Internet tools . This solution is based on the development of a web site that embodies a database of information about concrete and intelligent tools to deal with these data, as well as with inputs provided by the users.

As a result, the system can be regarded as a client-server architecture over the Internet, where a server hosts the site and the partners may access it via a common web browser (the client). Each partner can get data from the system, process data and store data into the database. The resulting site, which may run on Windows 9X/NT personal computers, comprises the following components:

- an HTTP server (that is a Web server);
- a set of HTML pages;
- a database developed in Access;
- a layer of Perl programs to access the database (via an ODBC driver) and build on-the-fly HTML pages for interfacing database management functions;
- a set of software tools delivered by partners as executable programs and a set of Perl programs to interface them; Perl routines run these modules and, if necessary, feed them with data extracted from the material database;
- a set of JavaScript programs, to run some of the procedures of the expert system (neural networks, knowledge based and numerical modules);
- a download area, where users can find: tools implemented by partners as DOS executables or spreadsheets; documents which explain how to run the tools and the modules of IPACS; documents which introduce users to the theoretical background of the IPACS tools.

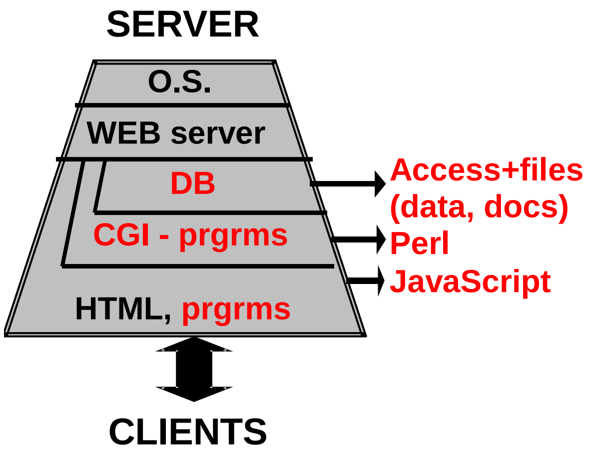

Figure 1. The layers of IPACS server

4 THE FUNCTIONAL ARCHITECTURE

The detailed design of the system comprises the following modules:

- culvert N.N.: this module receives from the users data that describe a culvert section (a wall on a slab), the ruling environmental conditions and the kind of concrete, and evaluates the cracking risk; it exploits neural networks to predict the cracking index; different networks may be used, on the ground of available data: users are driven by a graphical interface to select the most suitable net for their purposes;
- plate N.N.: it gets from the users data that describe a plate, the ruling environmental constraints and the kind of concrete, and evaluates the cracking risk; this module exploits the same techniques of the previous one;
- knowledge based & numerical modules: these procedures implement algorithms or rules of thumb with the purpose of studying cases not represented in the NN modules or to allow for a more engineering guided formalism of the early age response of the culvert and the plate cases; they comprise a module, exploiting both symbolic and neural processing, to evaluate the restraint factor for five main types of structure with several sub-cases; a graphical assistant to simplify three-dimensional structures for applying the proper case of the restraint evaluator; a thermal solver, to

calculate the temperature evolution of a semi-infinite concrete wall during the hydration process; a mono-dimensional solver for the viscoelastic problem;

- kind of structure: it implements a choice point, where the users are given support to choose the processing module that is most suitable for their problem;
- material database: a relational database that collects data about concrete; the database comprises a main archive, containing records which describe concrete-mixes, eleven archives containing data related to concrete components (water, cement, ...), and two archives for test data and processed data;
- material calibration module: an interface module that allows for the calibration of thermal and mechanical material models, by using data collected in the database; it can export data suitable to be managed by other processing modules. It may also export calibrated advanced material models to an external finite elements code, to solve the thermo-visco-elastic problem.

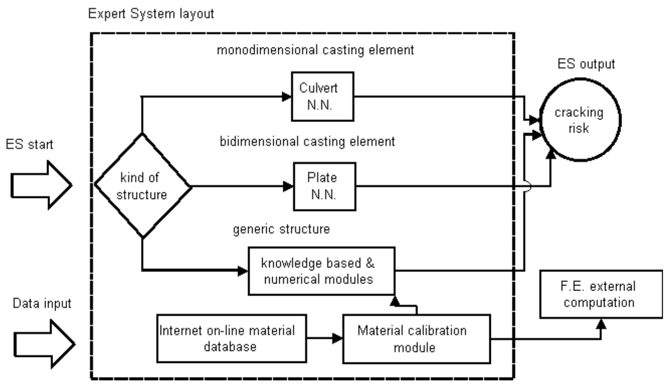

Figure 2. The functional architecture

5 THE NEURAL NETWORKS

Several processing modules within IPACS have been implemented via neural networks. Neural networks were chosen for IPACS to provide a tool able to safely provide the cracking risk evaluation, which requires experience and use of advanced mathematical tools to manage material behaviour; and able to incorporate also data coming from actual structural response: starting from examples, neural networks were expected to be able both to learn how, for example, concrete evolves and generates cracks; and also to deal with data different from those used for training them, and therefore to generalize what they had learned.

The neural nets used by IPACS have been trained on the ground of data generated by other tasks of the project or derived from literature (ACI curves, by the American Concrete Institute).

For the training, a commercial tool has been used (Neural Works Professional); after the training the nets have been exported from the off-line environment as C programs, then translated to JavaScript and embodied as JavaScript code in the web pages of the system; some modules exploit a combination of different nets.

Each net is a multiple-layer feed-forward net, with 3 or 4 fully connected node layers. The back-propagation learning scheme has been used for training the nets.

The input layers are made of nodes representing the input variables of the problem, whilst the output layer is made of one node, representing the result of the net: the modules for culverts and plates produce an estimation of the cracking risk; the modules for the restraint factor evaluation generate values for the restraint factor or slip factor.

One or more hidden layers are present with nodes that can be varied in number to reach the desired accuracy of the solution: the absolute average error ranges, according to checks performed on a set of test data, from 1.2% to 6.5%, and has been considered as an excellent result by the partners. These figures come from the comparison of the expected result and that forecasted by the network when processing cases never used for the training phase.

6 THE MATERIAL DATABASE

The so-called material database is a relational database that collects data about concrete under a consistent format.

The database comprises a main archive, containing records which describe concrete-mixes, eleven archives containing data related to concrete components (water, cement, aggregates, ...), and two archives for test data and processed data, that is data derived from test data by processing them (Fig. 3).

The Concrete mix archive can be regarded as the master archive: it contains the description of the different concrete mixes, as well as links to the other archives, which describe the results of tests (Test data and Processed data) or those of analyses of cement, silica, fly ash, and so on. The archives may contain data of different types:

- numbers (e.g. Cement content)
- strings (e.g. Responsible person)
- dates (e.g. Casting date)
- text files (descriptions of test methods)
- data files (e.g. temperature histories).

Several fields accept values coming from predefined dictionaries: these fields can be filled through graphical interactors, which increase system's user-friendliness.

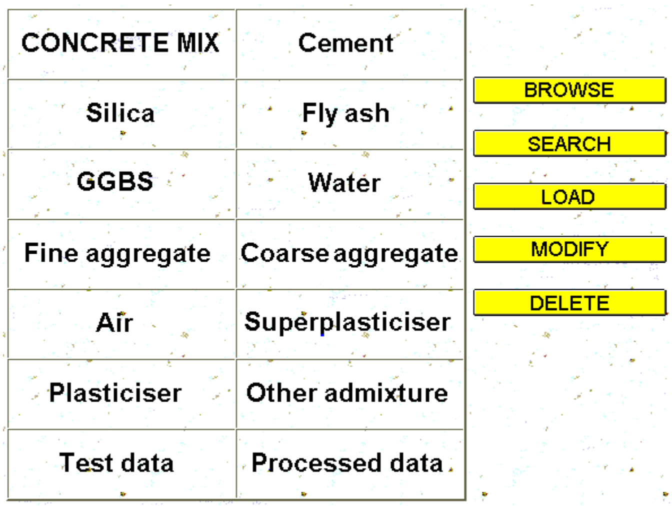

Figure 3. The control panel of the database

Common database functions are available: for each archive users may run the functions Load, for inserting new data, Search, for querying the archive and getting records which satisfy users' search criteria, Modify, for modifying data already recorded, Delete, for removing records from the archive, Browse, to look at the whole set of data; export functions allow to export both data and files.

Data files can be presented to the users in a simple graphic format to give an immediate idea of the time series and allow users to export these files when they need them for more sophisticated processing or plotting.

The access to the database is protected via user-names and passwords; passwords are encrypted and stored into a metadata base; a super-user of the system can add new users, delete existing users, and modify passwords; normal users are allowed to modify their own password and requested to provide it to access the system.

Automatic users can access the database: some procedures of IPACS can access the database to use data related to the concrete that users wants to deal with. In this case users do not need to input data related to the concrete, provided that some of the partners has already loaded them into the database.

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7 OTHER PROCESSING TOOLS

Graphical tools and written explanations support users throughout the system: whilst advanced users may directly use the most suitable path through IPACS, less experienced users will find different levels of explanations to select the tools they need, to feed the procedures with the right data, to load the database with properly formatted files and so on. The explanations can range from short in-line notes, to graphics, to hypertexts.

A graphical assistant supports users to simplify a three-dimensional structure to a two-dimensional one, when needed for applying 2D processing tools.

Other processing tools are integrated in IPACS and managed by the expert system: users are driven by the knowledge based module to use the proper tool. These tools, implemented via imperative programming and integrated into the expert system, are shortly described in the following.

A thermal solver implements a simplified formulation to calculate the temperature evolution of a semi-infinite concrete wall of a given thickness during the hydration process. It evaluates the average temperature increase in the wall (uniform) respect to the environment, through the use of a loss coefficient that incorporates the ability of the wall to dissipate heat.

A mono-dimensional solver for viscous-elastic problem calculates the stress evolution of a mono-dimensional concrete specimen due to restrained thermal loading.

A spreadsheet separates Thermal Dilation and Autogenous Deformation for a given free deformation test performed under a variable temperature history according to a measured/chosen/assumed development of the Thermal Dilation Coefficient.

A procedure to set up data to be run via the DIANA F.E.M. code computes age-dependent relaxation spectra associated to the Maxwell chain model.

Eventually, a program transfers semi-adiabatic calorimeter measurements (temperatures) to adiabatic temperature - and isothermal heat development, respectively. The program can also be used to provide a table with maturity-heat release data and to express the isothermal heat development in terms of continuous functions (the "Danish" or "Swedish" model).

8 HARDWARE AND SOFTWARE

The development of IPACS has been carried out on personal computers running the Windows operating system; several releases of the operating system have been exploited during the project's lifespan, from Windows 3.X to Windows 95/98 and NT.

The final release of IPACS has been installed on Windows NT computers and the final installation kit includes software for both NT and 95/98. Nevertheless, large parts of IPACS could be easily installed on Unix/Linux machines, provided that they run an HTTP server.

According to the initial choice of the Internet technology, IPACS requires an HTTP server to be run: the installation kit includes the free-of-charge Apache server and the instructions to install and run it on Windows PCs. Users are requested to run a common Internet browsers; the system has been tested on several releases of the most common browsers (Internet Explorer, Netscape Communicator, Opera).

IPACS includes HTML pages, which contain JavaScript programs, and a library of Perl programs. The Perl environment is included in the installation kit.

The neural networks have been trained within the software environment NeuralWare Professional Plus II and then saved as C routines and translated to JavaScript.

Some of the programs enclosed in IPACS have been written in FORTRAN and Visual Basic, while several modules available in the download area are Excel spreadsheets.

The material database is an Access archive, interfaced via the ODBC driver. Both the database and the HTML pages link documents in MS-Word, PDF, and zip format. Time histories within the Test data and Processed data archives are ASCII files formatted according to rules that are well explained within the pages of the database which are used for loading or browsing data.

9 CONCLUSIONS

IPACS has been conceived and developed as a system where experience on the hardening of concrete of different kind is available to support users of different background: material science, constitutive modeling as well as structural modeling and construction technology are all embodied in the system.

The software architecture has been developed to allow for a wide exchange of data and to ease further incorporation of models/data.

The expert system has been put on-line on the Internet since its first prototypical version. This enabled partners involved in IPACS to use and test it throughout the lifespan of the project.

In such way they have shared data, knowledge and comments from the early stages of the development and provided developers with fruitful feedback and comments for improving the system. Moreover, the access to a unique version of the system on the Internet enabled the partners to fill the database with data coming from tests performed by all of them.

The final release of the system is currently used by the partners both for the support to cracking risk evaluation and for storing and managing data about concrete.

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