Lancini, S., Lazzari, M., Masera, A., Salvaneschi, P. (1997). Diagnosing Ancient Monuments with Expert Software, *Structural Engineering International*, 7(4), pp. 288-291
Doi: http://dx.doi.org/10.2749/101686697780494392

Diagnosing Ancient Monuments with Expert Software

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Fig. 1 - San Dalmazio Tower, one of the monitored structures

Introduction

After the 1989 collapse of the Civic Tower of Pavia, Italy, the Italian government appointed a scientific committee to analyse the causes of the collapse and to check the state of other monuments in Pavia [1]. The masonry structures were carefully surveyed and subjected to a variety of in-situ and laboratory tests and stress analyses using finite element models. An extensive monitoring system was developed and installed in the cathedral and six medieval towers. Data collected by monitoring was processed and interpreted to verify the behaviour of each structure, and an expert system for on-line management and interpretation (KALEIDOS) was developed.

Monitoring System

Installed in 1989 in the Cathedral and on six Towers (*Fig. 1*), the monitoring system is linked via radio to a control center at the University of Pavia. The software package that manages the monitoring system helps to evaluate the reliability of the data acquired and to identify instrument failures.
[...].

Behaviour Analysis

The measurements gathered by the monitoring system are periodically recorded and stored in a database archive. These measurements are processed to analyse the behaviour of the monuments and to evaluate their safety. Correlations among measured quantities have been identified, and reference behaviour models for the most important risk assessment parameters have been defined. Specific thresholds for the on-line monitoring have been established.
[...]
Thus in January 1994, an interpretation software system run on a personal computer was connected to the monitoring system in the acquisition centre (Fig. 2). The software is an expert system capable of evaluating, explaining and filtering the data collected by the monitoring system. The system can alert safety managers and civil authorities through automatic telephone calls. The architecture of the checks carried out by expert software is shown in Fig. 3.
[...]

Validation of measurements

Validation of the measurements and the definition of their status are the first step in the interpretation process. The measurements are checked against pre-set thresholds, based on behaviour recorded in the past, at three different levels:
[...]

Activation state

The expert software uses the results of the checks on single measurements to evaluate the current state of each structural unit and to establish the so-called "activation state," which is when specific measured behaviour might actively effect the structure. Based on geometric reasoning, physical models and empirical knowledge, relationships among sets of measurements have been identified. These relationships guide the evaluation process of each single group of measurements. At this level, the system exploits knowledge about the significance and reliability of the instruments. In other words, it evaluates the data it receives.
[...]

Monument	Height(m)	Base (m)	Instruments and Quantities: causes/effects
Cathedral (Dome)	97.0	diam. 27.00	9 / 65 effects
S.Dalmazio Tower	40.1	4.9 x 4.9	5 / 10
Belcredi Tower	51.2	5.9 x 5.9	5 / 6
Clock Tower	39.2	5.5 x 5.5	5 / 6
Carmine Tower	65.6	9.4 x 7.5	5 / 6
Maino Tower	48.0	5.1 x 5.1	6 / 2
University Tower	38.5	5.4 x 5.4	6 / 5

Table 1: Characteristics of the monuments and their instrumentation

Strucutral units

Twelve zones and five sections (Figs. 4, 5) have been defined in the cathedral:
Zones: 1-8: Octagon of columns at the base of the dome; 9: top of the dome; 10-12: parts of the naves where some dilatometers are installed over cracks.
Sections: dome, drum, columns, base columns, nave.
The software evaluates the state of each zone; moreover, it evaluates the state of each sub-section, where a sub-section corresponds to the group of instruments resulting from the intersection of a zone and a section, e.g., the instruments on the columns of the zone 4.
[...]

Global synthesis

The synthesis process is the third step of interpretation performed by the software. The results of the analysis of single measurements, structural elements and anomalous processes are further analysed in order to derive the current state of each monument.
[...]

System interface

Users can access the processing results through a windows-based interface. The interface presents graphical representations of the objects (monuments, zones and sections, processes, measures) using a colour scale based on the object's status.
Text explanations of the analysis are displayed on the screen as well. Links are available to give users more information on specific details. Via the interface, the user can also activate management functions, such as accessing the internal database. Figs. 4-7 show some screen views of the system giving the state of the monument and the relevant explanation.
[...]

Artificial Intelligence

The system's interpretation engine is based on artificial intelligence (AI) concepts and techniques. In the design phase these concepts were used to gather and formalise expert knowledge using, e.g., causal networks of processes and qualitative modelling [3]. In addition, AI techniques such as rule-based processing, were used in conjunction with conventional techniques to implement representation and reasoning schemes.
[...]

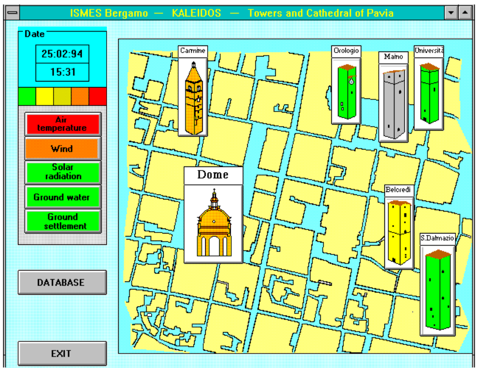

Fig. 2 - System control panel

Concluding remarks

Two towers in Pavia have been strengthened and some minor measures have been suggested for other towers. The expert software has performed an on-line interpretation of monitored data every six hours. Analysis of the results from January 1994 to September 1996 on a set of more than 6000 situations equalling about 850000 measurements, allows the following observations about the system's performance:

- Incorrect data is properly filtered, avoiding false alarms.
- Anomalies in the instrumentation are detected in a timely manner.
- The basic parameters used (thresholds, reference behaviours, significance and reliability values assigned to the instruments) have been confirmed and do not need revision.
- The behaviour of the structures complied with the reference forecast scenarios without identification of any anomalous processes (during testing, the system was checked against several collapse scenarios)..
- The growing database of situations evaluated by the system will be helpful for its future improvement, both for tuning new empirical or model-based strategies for for case-based reasoning techniques. The value of case-based reasoning techniques that highlight similarities between a current situation and past reference situations has been shown with other decision support systems [4].

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