An Expert System in The Domain of Fracture Mechanics

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INTRODUCTION

In the domain of fracture mechanics, as well as in many of the domains related to it, there is a number of issues entailing strong involvement of heuristics, such as: interpretation of nondestructive examination and material testing results, pressurized thermal shock analysis (Okamura, Yagawa, 1987), treatment of uncertainties, corrosion influence assessment, leak-before-break (LBB) analysis, etc. Numerical analysis alone, even when very complex, provides just a part of the total information necessary for reaching a valuable expertise, judgement and decision in the application domain. The expertise is necessarily linked to active role of humans, which cannot be avoided. However, current state of the art in the field of knowledge engineering (KE) and expert systems (ES), can offer a substantial complement to the "conventional" decision basis when dealing with some of the issues listed above.

The expert system described in this paper tackles the LBB-analysis, where the term "leak-before-break" describes behaviour of a pressurized component (pipe, vessel, etc.) during an actual or hypothesized failure caused by fatigue crack growth. Namely, LBB means that, once the crack has grown enough to penetrate the wall, only a leak occurs, leaving, under all possible circumstances, a substantial margin (e.g. in terms of safety and time for the component replacement/repair) between the leak occurance and final rupture of the component caused by the fact that the crack has reached the critical size ("break" - Fig.1). LBB is essential for inherent safety of pressurized systems and components (e.g. those in power plants), because hazards and technical remedies related to leak usually differ drastically from those of a break (Fig.2).

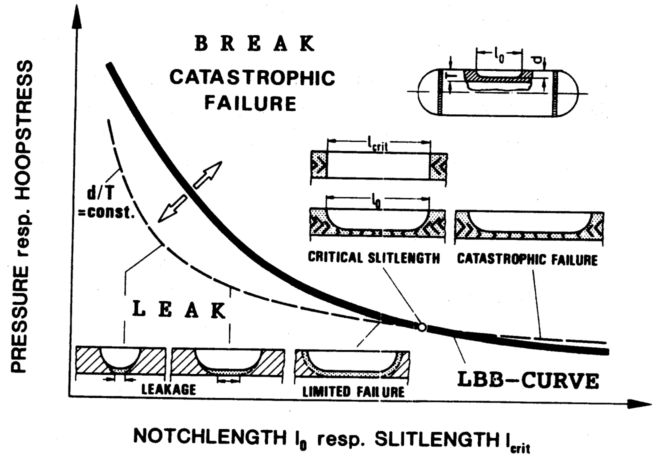


Fig.1 - A typical leak-before-break diagram

Design and practical development of the expert system for the LBB analysis has been related to other research efforts in the field of ES/KE applications in structural safety and integrity assessment, at the State Materials Testing Institute - MPA Stuttgart (see "Deep Knowledge ...", 1988). The issues of knowledge elicitation, knowledge representation and reasoning in the LBB expert system resulted to be of a great importance, so the work on these issues lead to development and application of a new and original concept (Jovanovic, 1989).

Fig.2 - A pressure vessel after break - MPA tests (Sturm, Stoppler, 1985)

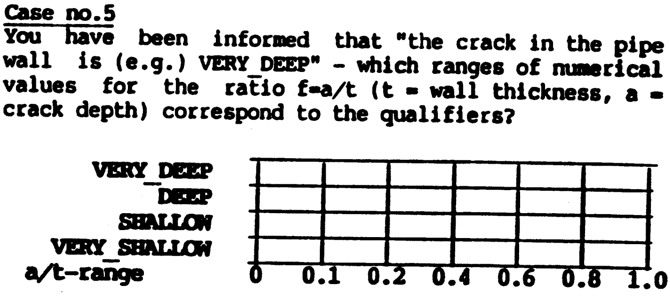
BASIC PARADIGMS OF THE SYSTEM

Several methodologies enable numerical analysis of the LBB behaviour (a survey of the methods can be found in works of Sturm and Stoppler, 1985 and 1987). However, many of them tend to be very conservative, or, when not conservative, to have large uncertainty margins. E.g., when applied to the same data base as the one used for the development of the LBB expert system, the methods and the data with which they have been applied, resulted in imprecision ranging between -30 and +40%, when predicting the critical bending moment for the circumferencial crack in large pipes. They have also entailed a relatively high degree of uncertainty in qualitative prediction of test outcomes (break / leak), confirming thus that the numerical methods cannot encompass all the factors relevant for the structural failure, such as material toughness, corrosion influence, stiffness of piping, nature of crack, temperature influence, etc. A way to analyze influence of these factors, is to include them as the "deep knowledge" (see "Deep Knowledge...", 1988) in the expert system, but this way has been abandoned here, in favour of a quicker and simpler one.

The adopted concept (Jovanovic, 1989) is based on analysis of analogy between the given case and the cases in the knowledge base (KB). Numerical and non-numerical information from, currently, about 50 tests (Sturm and Stoppler 1985; Sturm and Stoppler 1987; Stoppler and co-workers, 1987) is stored in the KB. Analogy in single factors (temperature, loading conditions, material toughness, etc.) is combined with results of the numerical analysis. Then, the relevant cases (if any!) are extracted form the knowledge base. "Relevant" are either those cases showing very high analogy with the analyzed one, or those being totaly different. The prediction *leak* or *break* is made accordingly. In this respect, the major difficulty is the definition of effective measures of similarity and proximity between the stored cases and the case which is to be analyzed. The definition of this measure concerns the generic, still opened, KE issue of characterizing real entities by analogy.

KNOWLEDGE ELICITATION

Three methods have been used in knowledge elicitation: organized inquiry, analysis of test reports and direct interviewing of the domain experts. The inquiry, containing a list of questions presented in form of tables (Fig.3), has been performed among the engineers of MPA and other institutions and companies (46 participants, see Jovanovic, Hassler, 1989), and it provided information regarding possibility distributions of numerical and linguistic variables used in the LBB analysis. Analysis of test reports provided the basic information (both numerical and qualitative) about the tests. Interviewing has been done with the MPA experts only, and its results have been used mainly for confirmation/redefinition of the heuristic rules (used in the ES) derived from analysis of reports.



Case no.5

You have been informed that "the crack in the pipe wall is (e.g.) VERY_DEEP" - which ranges of numerical values for the ratio f=a/t (t = wall thickness, a = crack depth) correspond to the qualifiers?

VERY_DEEP						
DEEP						
SHALLOW						
VERY_SHALLOW						

a/t-range 0 0.1 0.2 0.4 0.6 0.8 1.0

Fig.3 - A sample question from the inquiry (Jovanovic, Hassler, 1989)

KNOWLEDGE REPRESENTATION

In the Lisp version of the ES, the knowledge base is organized as a series of lists, containing both numerical and qualitative data. Numerical data taken into account are, e.g., geometry of the component, crack dimensions, working temperature, loads, material characteristics, etc. Qualitative information regards type of the crack (e.g. inside/outside, fatigue crack, welding defect,etc.), stiffness of the construction, etc. Rules, in this version of ES, are purely heuristic, e.g. *"when the crack is deep, then the chance of the failure mode leak is high"*. The terms like *deep* and *very high chance* are defined as trapeziodal fuzzy numbers (Jovanovic, Servida, Sauter, 1988), the parameters of which are derived from the inquiry - Fig.4. Technically, the solution is designed as an open architecture, shell free, intelligent module, interacting with the user in the search of the appropriate representation of various pieces of knowledge and in determination of its importance for the final conclusion.

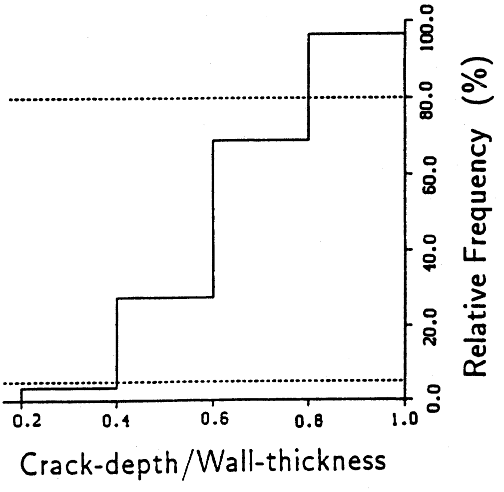
In the second version of the LBB expert system, the KEE^{TM}-shell was used. KEE^{TM} is a hybrid tool which joins the KE-methods (object-oriented programming, frame-based knowledge representation, rule-based reasoning, use of Lisp functions), with graphical oriented interactive possibilities for editing and browsing the knowledge bases as well as for a user-friendly presentation of the results. The frame in which the knowledge is stored, is an object-centered construction for knowledge representation, which puts together the static-descriptive attributes (i.e. features of an object) with dynamic-procedural attributes (i.e. behaviour of an object). The syntax of the rules within these frames is similar to natural language and allows the use of Lisp expressions, e.g.:

```
(if    (find (MIN.SIMILAR is in SIMILAR.MIN))
       (cant.find (MAX.SIMILAR is in SIMILAR.MAX))
       (the FAILURE.MIN of MIN.SIMILAR is ?X)
then do    (lisp (cond ((equal ?X 'LEAK) (unitmsg 'BREAK.ANSWER 'ANSWER.50))
           ((equal ?X 'BREAK) (unitmsg 'LEAK.ANSWER 'ANSWER.50)))))
```

REASONING BY ANALOGY

The main task of the reasoning process is the intelligent recognition of analogy/similarity between the analyzed case and the cases in the knowledge base. To each piece of knowledge regarding the influencing factors, is attributed a weighting factor, the initial value of which is provided by the domain expert, but the value of which can be reviewed interactively. Analogy between numerical data is defined as a combination of the weighting factors and the algebraic ratio/difference. Obviously, the operating temperature of 120°C is more similar to 150°C than to 30°C . Analogy in qualitative data is more difficult to define. So far, the issue in the LBB expert system is tackled either by direct specification of the granularity of the descriptors (*very corrosive* is more similar to *corrosive*, than to *neutral*), or by assigning membership functions to the descriptors (Jovanovic, Hassler, 1989) - Fig.5. Thus, the analogy/similarity can be "quantified" and, later on, compared. The search for analog cases is however, still "unintelligent", as the limited number of cases in the knowledge base still allows to compare the actual case with each of the stored cases. This issue, however, has to be improved further on, as an increase of the number of cases in the knowledge base is expected.

Reasoning has two levels: the one of the pre-established production rules and the one of the self-generated and "implicit" rules. Its main result is the diagnosis/prediction of the structural state, in terms of *leak*, *break*, *no failure* and *prediction impossible* (not any). In addition, semantic (linguistic) probability estimators (e.g. *very high chance*, *meaningful chance*, *it may be*, etc.) are assigned to ES outcomes, accordingly to how strong the analogy between the analyzed and the reference case(s) was. Transition between the semantic and numerical probabilities is obtained by means of fuzzy algebra (Jovanovic, Servida, Sauter, 1988; Zimmermann, 1987). Precision of the system can be tuned through interactive definition of the analogy significance limits. Thus, if a high certainty of answers is required only "sure" analogies will be identified, with the consequence that the probability of not finding the significant analogues increases (see Tables 1 and 2). Coupling between the engineering numerical calculations and the symbolic analysis used in reasoning is done so that the numerics is invoked from Lisp, as Fortran subroutines.



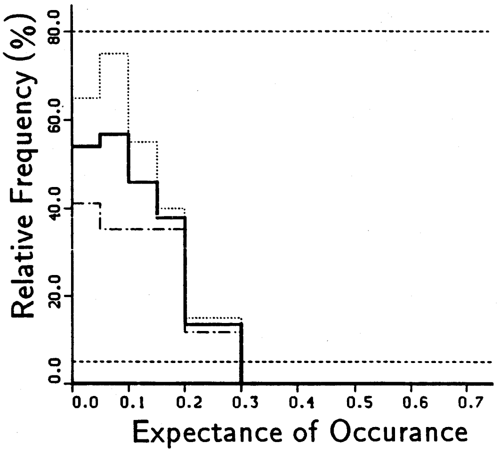


Fig.4 - Results of the inquiry showing the link between term "very deep crack" and the ratio crack-depth/wall-thickness

Fig.5 - Results of the inquiry showing the link between the estimator "unlikely" and the expected probability of occurance (thick line)

PRACTICAL IMPLEMENTATION OF THE SYSTEM — LISP VERSION

The Lisp-version of the system has been programmed in the frames of a small project (Hassler, 1988) performed at MPA Stuttgart. In this version, the user is supposed to provide standard data regarding the component (loads, materials, known state of defects), as well as the evidence (description of the current situation), directly. The user is also supposed to provide inputs relevant for the definition of the representation frame, granularity and semantics, as well as for the definition of uncertainty in the information given as input to the system.

The results of the systems verification, performed on the MPA LBB full-scale tests internally pressurized pipes, $\phi = 800\ mm$, exposed to bending and containing a circumferential defect (see Stoppler and co-workers, 1987), are shown in Tables 1 and 2. The verification is done in such a way, that each time one of the tests has been taken out from the knowledge base and then analysed by the ES on the basis of the tests remaining in the knowledge base. The verification shows that optimization of the weighting factors and narrowing of analogy significance limits lead to higher precision of predictions, but contemporary, to reduction of number of cases in which the system provides an answer (Table 2).

Table 1: LBB expert system results, for unoptimized weighting factors and the analogy significance limits 0.3 and 0.7

Test Nr.	Test result	ES prediction	Probability descriptor
BVZ110	LEAK	BREAK	'meaningf.chance"
BVZ120	LEAK	LEAK	'meaningf.chance"
BVZ130	LEAK	LEAK	'meaningf.chance"
BVZ140	LEAK	BREAK	'meaningf.chance"
BVZ150	BREAK	BREAK	'meaningf.chance"
BVZ040	BREAK	BREAK	'meaningf.chance"
BVZ050	BREAK	LEAK	"it may be"
BVS060	BREAK	BREAK	'meaningf.chance"
BVS070	LEAK	LEAK	'meaningf.chance"
BVS080	BREAK	LEAK	'meaningf.chance"
BVS102	BREAK	LEAK	'meaningf.chance"
BVS050	BREAK	BREAK	'meaningf.chance"
Nr. of predictions vs. nr. of analyzed cases			12/12
Exact Predictions			58%

Table 2: LBB expert system results, for optimized weighting factors and the analogy significance limits 0.1 and 0.9

Test Nr.	Test result	ES prediction	Probability descriptor
BVZ110	LEAK	not any	—
BVZ120	LEAK	LEAK	'meaningf.chance"
BVZ130	LEAK	not any	—
BVZ140	LEAK	not any	—
BVZ150	BREAK	not any	—
BVZ040	BREAK	not any	—
BVZ050	BREAK	BREAK	'meaningf.chance"
BVS060	BREAK	BREAK	'meaningf.chance"
BVS070	LEAK	not any	—
BVS080	BREAK	not any	—
BVS102	BREAK	not any	—
BVS050	BREAK	not any	—
Nr. of predictions vs. nr. of analyzed cases			3/12
Exact Predictions			100%

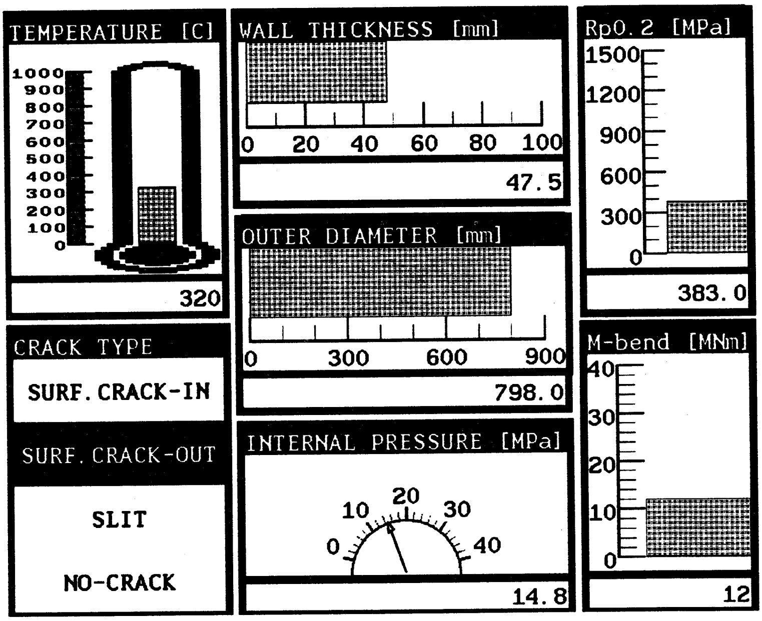
PRACTICAL IMPLEMENTATION OF THE SYSTEM — KEE^{TM}-VERSION

So far, the practical implementation in KEE^{TM} differs from the one in Lisp, mainly due to the introduction of more sophisticated graphic oriented, user interface (mouse, menues and so-called active images), Fig.6. Also, in addition to the failure mode prediction (*leak/break*) the system, in case of a leak, tells the threshold values where a break is to be expected, i.e. under which loading conditions will a catastrophic failure occur.

CONCLUSIONS

The LBB expert system has been designed and developed as a practice oriented, KE-based engineering tool. Although simple, its first results appear to be good, and allow to expect that, with future developments, will be further improved. Its practical use should help in enhancing the structural integrity assessment and life extension analysis for pressurized components. The efficiency of the system is partly tested in the experiments of MPA, while further verification in practice should be done in collaboration with industry.

Fig.6 - One of the screens in the KEE^{TM}-version of the expert system



TEMPERATURE [C]
320

WALL THICKNESS [mm]
47.5

Rp0.2 [MPa]
383.0

OUTER DIAMETER [mm]
798.0

CRACK TYPE
SURF.CRACK-IN
SURF.CRACK-OUT
SLIT
NO-CRACK

INTERNAL PRESSURE [MPa]
14.8

M-bend [MNm]
12

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