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Computer-Aided Fatigue Design of Steel Structures

Conception assistée par ordinateur de structures soumises à la fatigue

Computergestützter Entwurf bei ermüdungsbeanspruchten Stahlbauten

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SUMMARY
A pilot expert system for the fatigue design of steel structures is presented. This system was developed for use with the ECCS Recommendations for the Fatigue Design of Steel Structures (1985). The system helps designers identify appropriate detail categories and also, alternative designs are proposed if a detail is not satisfactory.

RÉSUMÉ
Un système expert pilote pour la conception assistée par ordinateur de structures métalliques soumises à la fatigue est présenté. Le système a été développé pour être utilisé avec les recommandations de la CECM pour la vérification à la fatigue des structures en acier (1985). Il permet aux ingénieurs de classifier de façon appropriée un détail de construction, et propose des solutions de rechange au cas où un détail n'était pas satisfaisant.

ZUSAMMENFASSUNG
Ein Prototyp eines Experten-Systems zum Entwurf von ermüdungsbeanspruchten Stahlbauten wird vorgestellt. Das System wurde entwickelt zur Anwendung der EKS Empfehlungen für die Bemessung und Konstruktion von ermüdungsbeanspruchten Stahlbauten (1985). Es dient dazu, Konstruktionsdetails in die richtigen Kerbgruppen einzuordnen und, falls nötig, Alternativen zu einem gegebenen Konstruktionsdetail vorzuschlagen.

1. INTRODUCTION

Good fatigue design requires an understanding of many factors. Although fatigue-design guidelines are numerous, many are not appropriate for assessment of large steel structures. During a fatigue assessment, designers can become confused by the complexity of the problem and the variety of available solutions.

Recently, parameters which are most important to large steel structures were identified and as a result, many countries simplified code provisions. International harmonization was achieved in 1985 when the European Convention for Constructional Steelwork (ECCS) published "Recommendations for the fatigue design of steel structures" [1]. This publication is beinq used as a basis for revising many national design guidelines.

Although the ECCS document represents an important contribution toward simplifying the designer's task, some problems remain. Work associated with implementing the Recommendations revealed that when using the document, designers may not always make the same judgements as would experts.

This paper begins with a summary of the ECCS Recommendations and a discussion of areas where expert judgement is needed. Next, expert systems are described and evaluated within the context of civil engineering. Finally, a pilot expert system, developed for use with the ECCS Recommendations, is introduced.

2. ECCS RECOMMENDATIONS FOR THE FATIGUE DESIGN OF STEEL STRUCTURES

These Recommendations are the result of six years work by members and guests of ECCS Committee TC6 under the chairmanship of Prof. Hirt, the Swiss Federal Institute of Technology, Lausanne. The fatigue assessment employs the following four fundamental parameters : number of stress cycles, detail category, fatigue strength (in terms of stress range), and applied stress range. The first three parameters can be related to each other by means of the following relationship :

$$\Delta\sigma_R = DC\left(\frac{2\cdot 10^6}{N}\right)^{1/3} \qquad (1)$$

where DC is the detail category, $\Delta\sigma_R$ is the fatigue strength and N is the number of stress cycles.

The Recommendations propose that the designer compares the fatigue strength of a given detail, $\Delta\sigma_R$, at a given number of stress cycles with the fourth parameter, applied stress range, $\Delta\sigma_e$, using partial safety factors.

$$\gamma_s\ \Delta\sigma_e < \frac{\Delta\sigma_R}{\gamma_m} \qquad (2)$$

where γ_s and γ_m are partial safety factors determined from a reliability analysis, or from the authority having jurisdiction.

Therefore, a procedure for details requiring a fatigue assessment could be carried out according to the following (simplified) steps :

STEP 1. Classify a given detail according to its detail category through reference to diagrams and descriptions in the Recommendations.

2. Taking the required fatigue life (number of stress cycles) and the detail category, determine the fatigue strength in terms of stress range according to Equation (1).

3. Calculate the applied stress range using loading information.

4. Using appropriate safety factors, test the requirement described by Equation (2).

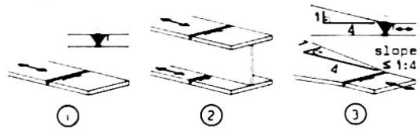
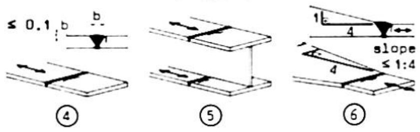
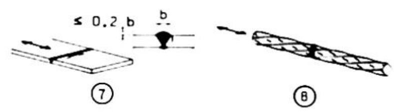
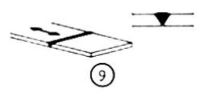
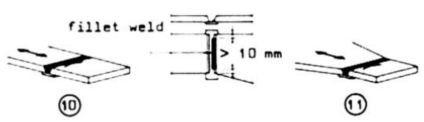
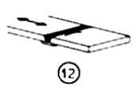
5. If the requirement described by Equation (2) is met, select next detail for assessment and return to Step 1.
6. Select an alternative detail design. This involves measures such as revising the design in order to change the detail category, increasing plate thickness, employing fatigue strength improvement methods (which should be verified through laboratory testing), or any combination of these measures. Repeat assessment from Step 1.

After discussions with design engineers who use these Recommendations, two problems were identified. The first problem is associated with detail classification, Step 1. Some designers have difficulty identifying the most appropriate category for the detail being assessed. The diagram, for example see Figure 1, corresponding to the correct detail category in the Recommendations may not resemble the detail. Occasionally, a non-expert may decide erroneously that another detail category is more appropriate. Errors due to this problem can have very serious consequences.

The second problem occurs at Step 6. If a fatigue assessment reveals that the detail is unsatisfactory, the most appropriate alternative detail design may not be chosen. Errors due to this problem are caused by a lack of practical experience in detail design when fatigue assessments are necessary. A design engineer may not be capable of good fatigue design. Such difficulties result in unnecessarily costly structures.

TABLE B2.3 : TRANSVERSE BUTT WELDS

Classification of typical constructional details. The arrow indicates the location and the direction of the stresses for which the stress range is calculated.

<table>
<tr><th>DETAIL CATEGORY</th><th>CONSTRUCTIONAL DETAILS</th><th>DESCRIPTION</th></tr>
<tr><td>112</td><td>All welds ground flush to plate surface parallel to direction of the arrow.
</td><td rowspan="4">Without backing bar
(1) Transverse splices in plates, flats and rolled sections.
(2) Flange splices in plate girders before assembly.
Details (1) and (2) may be increased to Category 125 when high quality welds, proven free of detectable discontinuities are used, see Appendix B3.
(3) Transverse splices in plates or flats tapered in width or in thickness where the slope is not greater than 1:4.
(4) Transverse splices of plates or flats.
(5) Transverse splices of rolled sections or welded plate girders.
(6) Transverse splices in plates or flats tapered in width or in thickness where the slope is not greater than 1:4.
Requirements for details (4), (5) and (6) :
- The height of the weld reinforcement to be not greater than 10 % of the weld width with smooth transitions to the plate surface.
- Welds made in flat position.
(7) Transverse splices of plates, flats, rolled sections or plate girders. The height of the weld reinforcement smaller than 20 % of weld width.
Requirements for details (1) to (7) :
- Weld run-off pieces to be used, subsequently removed and plate edges ground flush in direction of stress.
- Welds made from two sides.
(8) Butt welds in concrete reinforcing bars.
(9) Butt welds made from one side only.</td></tr>
<tr><td>90</td><td>As-welded.
</td></tr>
<tr><td>80</td><td></td></tr>
<tr><td>36*</td><td></td></tr>
<tr><td>71</td><td></td><td rowspan="2">With backing bar
(10) Transverse splices.
(11) Transverse butt welds tapered in width or in thickness where the slope is not greater than 1:4.
Requirements for details (10) and (11) :
- The fillet weld which attaches the backing bar to terminate more than 10 mm from the edges of the stressed plate.
(12) Transverse butt welds when a good fit cannot be guaranteed or when backing bar fillet welds are terminated closer than 10 mm to the plate edge.</td></tr>
<tr><td>50</td><td></td></tr>
</table>

* : see Clause B1.07

FIGURE 1 : Example of tables of constructional details contained in [1].

3. EXPERT SYSTEMS FOR ENGINEERING DESIGN

3.1 Characteristics of expert systems

Expert system development involves placing all information pertaining to a domain in knowledge bases. Knowledge bases contain both facts and logical relationships between data groups. In addition, knowledge bases may have rules formulated using an expert's experience in the domain. Some of this experience-developed knowledge is termed heuristic knowledge, and it is used principally to identify a group of good solutions from a large number of possible solutions. Therefore, expert systems are most useful when a detailed analysis of all solutions is not justified.

Expert systems control their knowledge bases by means of inference engines. Inference engines are programs which contain procedural information on how knowledge bases are used to find solutions to given problems. No facts or logical relationships concerning any domain are held in inference engines. If not enough information exists in the knowledge base, the user is consulted automatically. Most inference engines have explanation facilities which backtrack through the knowledge base in order to explain to the user the reasoning behind a particular question or conclusion.

Most inference engines are independent of the knowledge base and consequently, they can be applied to many problems. However, the inverse is not true; knowledge bases, including their heuristic information, are constructed for specific inference engines. Typically, inference engines are enclosed in environments which facilitate user interface during problem solving. Also, editors for creating and changing knowledge bases are included. Such environments are called shells or expert-system development tools.

The results provided by an expert system normally take the form of conclusions which are based on deductions made while the inference engine was processing the knowledge base. More than one conclusion may be offered; concepts of likelihood can be employed to indicate the most probable. More sophisticated tools provide indications of the sensitivity between facts supplied and conclusions drawn.

In civil engineering, expert systems are particularly applicable because a large proportion of civil engineering tasks require the use of knowledge gained through experience. Expert systems synthesize facts and heuristic knowledge, thereby providing useful design aids for civil engineers.

3.2 A pilot expert system for fatigue design

A pilot expert system has been developed in order to improve the quality of fatigue design using the assessment procedure described in Section 2. Development of this system involved the following phases :

PHASE 1. Creation of a paper model for detail classification using information given in the ECCS Recommendations.

2. Generation of case studies; alternatives have been priorized for situations where details, classified in Phase 1, fail the fatigue assessment.

3. Analysis of case studies; formulation of general rules for the selection of alternative designs.

4. Transfer of the paper model and rules for alternative designs to a computer model using an expert-system development tool called EXSYS [2].

5. Testing and verification of the computer model.

PHASE 1 - A paper model of approximately one fifth of the details, or half of Figure 1, is shown in Figure 2. Detailed criteria determining the finest divi-

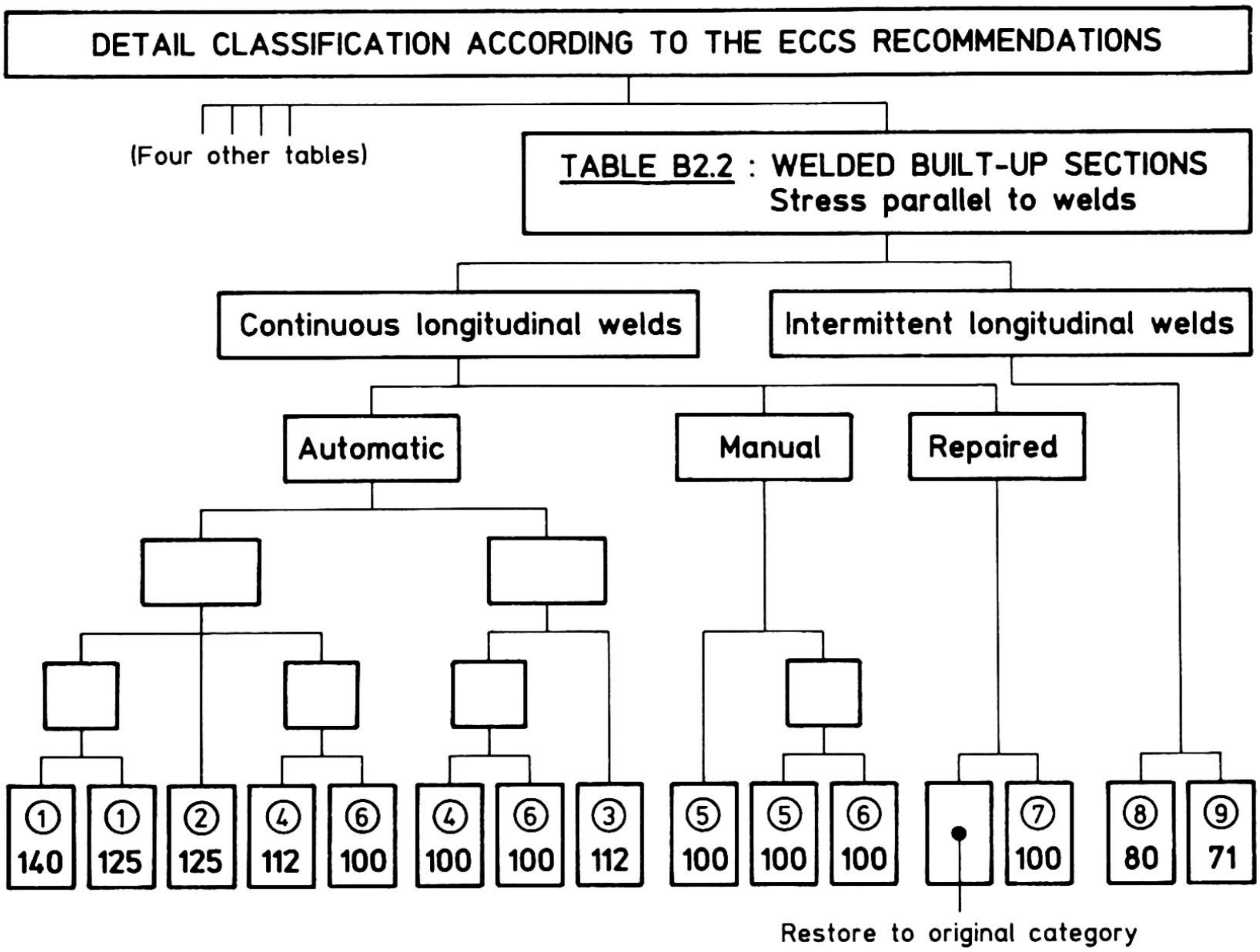


FIGURE 2 : Part of the paper model of the ECCS detail classifications [1].

sions, such as the presence of stop-start conditions, inspection criteria and weld type, are not shown. Each box at the bottom of Figure 2 represents a particular detail. The circled number in the box refers to the detail number defined in the Recommendations and the other number gives the detail category used during the assessment, see Equation (1). The structure of Figure 2 is analogous to an inheritance tree whereby the boxes in the bottom portion of the figure inherit the characteristics of their so-called parents higher up in the tree.

PHASE 2 - Generation of case studies was performed using an expert who selected and priorized alternatives for every detail in the paper model. The first author served as the expert. A description of this exercise is shown on Figure 3 for one detail in the tree. The detail which is presumed to fail the fatigue assessment is shown by the symbol, x, and alternative detail designs are numbered from highest to lowest priority.

PHASE 3 - The most obvious characteristic of the choice of alternatives is that, for a given case, whole sections of the paper model are not considered. This is due partly to detail compatibility. For example, a welded beam cannot be replaced by a longitudinal attachment, or a shear stud.

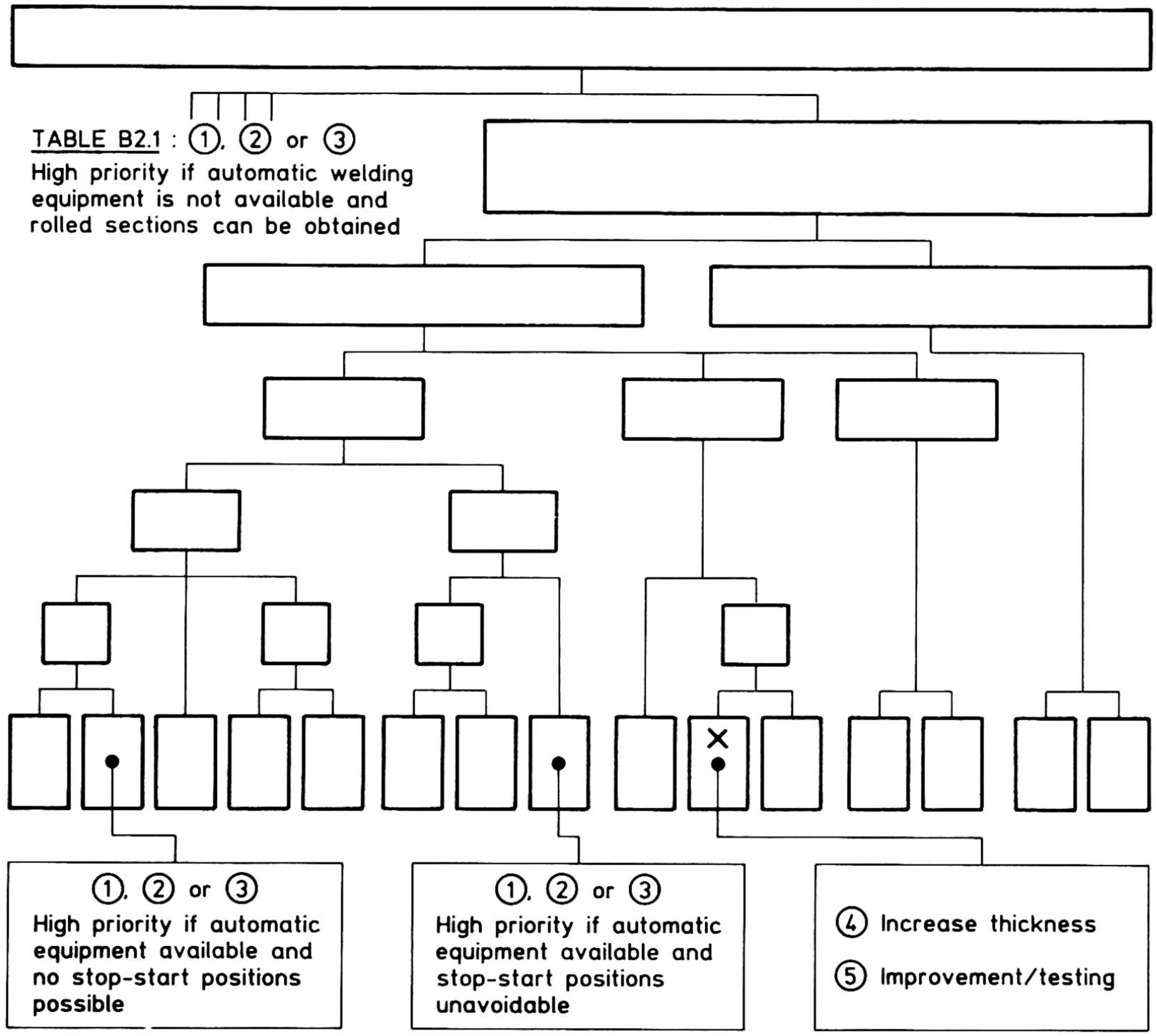


FIGURE 3 : Generation of alternative detail designs, numbered according to their priority given that a detail, shown by an x, fails the fatigue assessment.

Additional criteria were used to eliminate compatible designs. For example, if quality assurance cannot be guaranteed during fabrication, then all details which require high quality welding are not considered. Other criteria such as access for two-sided welding and the availability of automatic equipment often determine the number, type and priority of alternatives.

Details were priorized using criteria which are not described explicitly in the Recommendations, and which non-expert designers may not employ. Two alternatives, increasing thickness and fatigue-strength improvement including testing are not included in the classification model, Figure 2. Since these alternatives are possible for the large majority of details, the alternative-solution space is really three dimensional and therefore, the problem becomes more difficult.

However, some simplifications are possible. The improvement/testing alternative was always the lowest priority and increasing thickness was usually second lowest. Generally if a detail fails a fatigue assessment, it is best to investigate another detail before an attempt is made to keep the original detail through increasing plate thickness or through prototype testing and fatigue-strength improvement. This type of knowledge was used to assign values to alternatives. These values help to rank the alternatives from highest to lowest priority.

Thus heuristic knowledge was used for two purposes. The first helped to reduce the number of possible solutions, and the second helped to priorize the remaining alternatives. In most cases, eleven rules were being employed repeatedly during the selection of alternatives. These rules formed the basis of the heuristic portion of the knowledge base.

PHASE 4 - Transfer of the paper model and selection criteria to a rule-based expert system was achieved using a development tool called EXSYS [2]. Rules were constructed for classifying details, for generating alternative designs, for enabling user intervention and for providing control. A total of 154 rules (IF...THEN...ELSE...) make up the knowledge base. The inference engine employed backward chaining [2] for examining the rules and for interrogating the user. The system can be run in two modes - detail classification and alternative search. Figure 4 summarizes the principal components of the system.

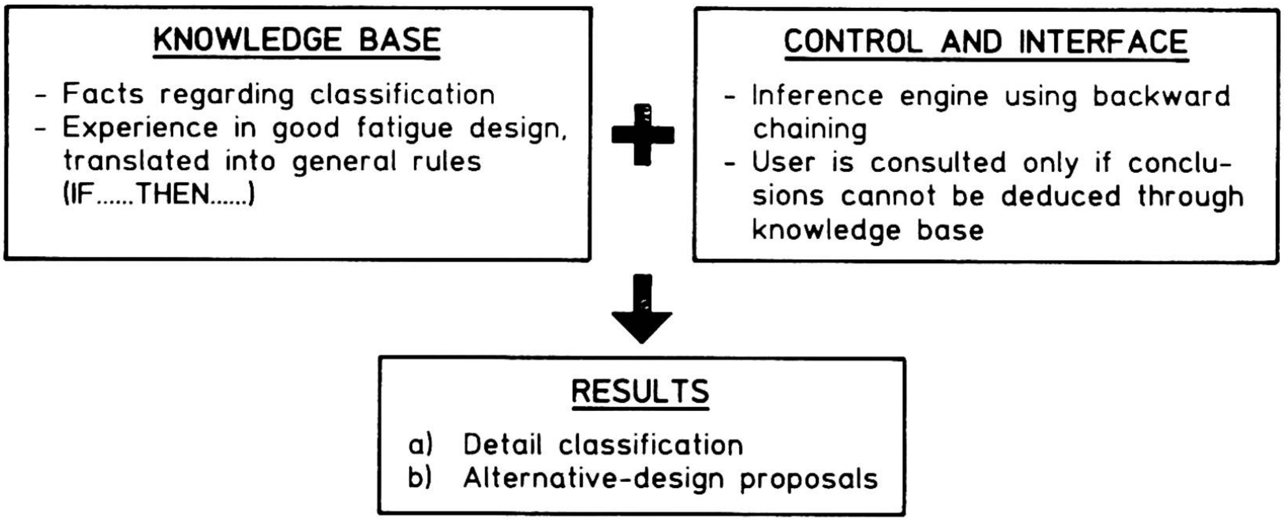


FIGURE 4 : Components of an expert system for fatigue design.

During detail classification some information, such as the ability to ensure adequate quality control, are stored for use during the generation of alternatives. This information helps to avoid situations where the user is asked needless questions. For example, if the original detail is one which requires special quality-control measures, the user will not be asked about quality during the generation of alternatives. It is assumed that if special quality-control measures are possible for one detail, they are also possible for another.

Before generating alternatives, the user is asked whether the original detail failed the fatigue assessment by a great deal, little, or half way between these extremes. If the fatigue assessment fails by a great deal, possible alternatives having high fatigue strengths are favoured. Conversely if the assessment fails by a little, the alternative detail design which increases the thickness of the original detail may be given a higher value.

Occasionally, alternatives do not include retaining the original detail under any circumstances. This is the case where the original detail has a low fatigue strength and there is another detail which is always a better design. In such cases, alternatives involving increasing thickness and testing/improvement are provided for the stronger detail.

During the search for alternatives, the user is given the opportunity to diverge from the opinion of the expert who helped develop the model. This is achieved by changing coefficients which govern the viability and priority of some alternatives. The user is asked if a personal opinion regarding a certain factor differs from the expert's opinion. If so, a new coefficient is requested.

PHASE 5 - Testing and verification is in progress. The information provided by the system compare well with the choices of the expert. Several fatigue experts are evaluating the recommendations provided by the system. This stage will be followed by non-expert evaluations in order to provide stimulus for creation of a clear and simple user interface.

Throughout the testing stages, some work will concentrate on the coefficients which are employed to select and to priorize alternatives. More work is needed to determine a physical meaning for their values in order to give the user an indication of the influence of certain factors on recommendations.

4. CONCLUSIONS

1. Even when modern codes are used, a certain amount of expert knowledge may be needed to create good fatigue designs.
2. Expert-system knowledge bases provide an effective way of formalising expert capabilities in civil engineering through synthesizing facts and design strategies.
3. A pilot expert system which aids good detail design was developed successfully using the ECCS fatigue-design document.
4. Further work, such as testing the system using several fatigue experts, is needed before the system can be offered for general use.

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