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The need for deep knowledge in expert systems for preliminary structural design

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Expert systems are being developed for a large number of application areas in design. Most of these concentrate on one stage of the design process such as conceptual design, preliminary design, detailed design or design documentation. However, they are still not being widely accepted as practical tools in industry. This is generally attributed to inadequate performance; the solutions generated by the expert systems are not as good as those from human experts. The failure is mainly due to the inability to encapsulate the expertise comprehensively as heuristics, since these are not capable of representing the underlying fundamental engineering principles. This is especially true in structural design as each of the designs required has certain features which are unique to that problem. The question is then raised; *'Is it possible to obtain specific solutions from a general set of rules?'*. It is concluded that expert systems for design can only work if they encapsulate deep knowledge.

Expert systems are being actively considered as tools for use in structural design. It is argued here that, while they do indeed offer the prospect of great assistance with the design process at some stage in the future, at the moment their significant use is restricted by an inadequate representation of the design process itself. Currently, expert systems serve as tools for those attempting to sort out the logic of design, in much the same way that the introduction of matrix methods and computers gave tools to those interested in the rationalization of analysis procedures in the 1960s.

Some of the examples presented herein are from our own studies on prestressed concrete bridge design, but the principles are reflected in most areas of structural design.

Two definitions are essential for the requirements of structural design.

Analysis

'Analysis' is the procedure by which the distribution of forces, stresses and deflections within a structure are determined. It is the subject that most engineers are taught at university or college where, for historical reasons, it is given an importance far in excess of its true value to design engineers. The most important point to be considered here is that the structure configuration must be known already; analysis is the process by which structural adequacy is checked.

Design

'Design' is a word that means many different things, depending on the context, so to avoid any confusion, we define 'Structural design' as the selection of the dimensions and properties of a structure which is required to perform a specific task. To quote Naaman[1]:

> ''In civil engineering strucutres, design involves the selection among a large array of possibilities of many particulars, such as structural layout, the shape of a member, the structural material, and even the construction process.

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Within each step the design deals with the actual versus the ideal and at different levels of details. Although design does not necessarily imply finding the optimum solution, it certainly aims at being within an appropriate range of the optimum. Because of its inherent nature of dealing with unknowns and because infinite combinations of possibilities exist, design is mostly an iterative process. An efficient design is one in which the number of iterations is reduced to a minimum. This often depends on the experience and skills of the designer''.

It is this process that the designers seek to understand and mimic in an expert system. It is reasonable to ask what changes have been brought about in design methods as a result of computer techniques. The answer is surprisingly few. It is now feasible to re-analyse quite complex structures in a few minutes on a desk-top computer, so many designs are now performed on a 'Design by repeated analysis basis', but this has, arguably, led to a poorer understanding of the underlying principles, rather than a better one, and is at the root of the problem outlined by the Institution of Structural Engineers report into the teaching of structures[2]. 'Computer Aided Design', as most frequently met in design offices, is used primarily as a draughting tool, rather than as a true design tool.

THE STRUCTURAL DESIGN PROCESS

The design process is now considered in more detail, and studied to see where the use of a rule-based expert system may be of value.

Structural design can usually be broken down into four components.

1. Conceptual design
2. Preliminary design
3. Detailed design, and
4. Design documentation

In each of these phases, expert systems can play a role, but that role will differ between each case.

Conceptual design

In this phase the engineer considers various options for structural layout and construction method. Spans would be chosen, where they are not already proscribed by the site, as would material (e.g. steel or concrete), cross-section form (e.g. beam and slab or spine beam) and construction method (e.g. precast or in-situ). Relatively few calculations would be performed, engineers relying on their judgement of what would be suitable.

The knowledge required at this stage consists mostly of qualitative reasoning. Hence the expert system for conceptual design will be similar to diagnostic expert systems. However, there is a major difference between the two kinds of expert systems; in expert systems for conceptual design, the goal is not uniquely defined. The goal reached in any design problem is determined by the components of the structure[3].

Hence, the development of expert systems for conceptual design will be a much more complex task since there are a considerable number of goals and subgoals to be achieved which are not predefined. This is further complicated by aspects like aesthetics which are highly subjective; this is addressed with the aid of multiple experts[3].

Preliminary design

The conceptual design phase will have produced for the engineer a (small) range of possible options, such as spans, structure type (e.g. spine beam or beam-and-slab) and materials (e.g. reinforced concrete or steel plate girder). Ideally one option will have been selected as the most likely design to succeed. In the preliminary design phase the engineer will take one of these structural forms, and put more detail onto the design. If a spine beam design has been chosen, the number, thickness and inclination of the webs must be determined. Flange thicknesses, widths and other controlling dimensions must be picked. For prestressed bridges some idea of the prestressing forces and eccentricities must be found, and if the structure is indeterminate, the designer must decide how secondary moments are to be considered. The construction sequence will have to be determined, as this may have a significant impact on the overall bending moments in the structure.

The preliminary design of structures is an area that is currently being pursued in expert systems research. Early examples are HIRISE[4] and ALLRISE[5]. The approach taken in these projects have influenced many other expert systems developed subsequently such as INDEX[6]

It is notable that most of these expert systems have failed to gain a significant acceptance from the industry as practical design tools. This can be attributed mainly to the dependence of these systems on the shallow heuristic

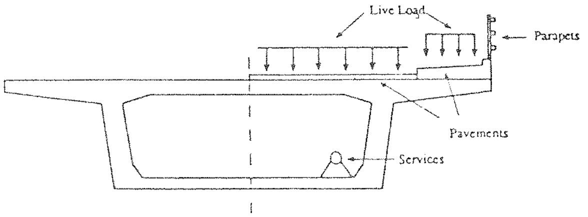

FIG. 1 TYPICAL SPINE BEAM CROSS-SECTION

knowledge incorporated either as rules or databases which are used for generating preliminary solutions.

As observed by Inder et al.[7] at preliminary design the expert's way of tackling the problem is different from that of novices or near-experts. Experts deploy their skill to balance the influences of a number of aspects; thus they choose a strategy that gives them the maximum chance of compensating for failures at the subsequent detailed design stage. Hence the experts spend more time in the symbolic domain while carrying out only a small degree of equation solving for concept clarification.

Conversely, as pointed out by Hoeltzel & Chieng[8], novice designers work in a different manner; the less knowledge they have, the greater the proportion of the time they spend on computations typically manipulating equations involving trade-offs in order to make judgement concerning the validity of various design alternatives. This process often leads to "*design by repeated analysis*" with feedback from the successive analyses as the "*redesign knowledge*", to modify the preliminary solutions.

Most of the expert systems developed for the preliminary design have to rely on redesign knowledge to modify the preliminary solutions. This has made redesign an active area of research. This is clear evidence that the solutions generated by the expert systems based on the shallow heuristic knowledge are not capable of matching the expert's problem solving ability, but they rather tend to follow the approach by near experts or novice designers.

Hence the most important requirement for the preliminary solutions generated by a real expert system is that they should be comparable with the expert's own solutions. This means that these preliminary solutions should either have taken account of all the constraints or have adequate provision to take account of constraints which have to be overlooked due to complexity or uncertainty, so that the preliminary design solution will succeed at the subsequent detailed design stage. This is an ideal expectation which is difficult to fulfill with the solutions generated based on heuristics alone. It requires a thorough understanding of the interaction of constraints and the influences of these interactions on the design parameters.

The ability of experts to outline good preliminary solutions is often considered as a kill that they have gained over a long period of time. Hence, it is difficult to grasp this knowledge using traditional knowledge elicitation techniques. The success of developing practicable expert systems for preliminary design, therefore, depends on seeking alternative ways to match this ability of the experts. This needs detailed studies into structural design to unravel the fundamental reasoning behind the decisions made by the experts when performing preliminary design.

The detailed study for this phase can be carried out under the following topics. Requirements for expert system on prestressed concrete beam are cited to highlight the requirement of detailed study.

1. Explicit identification of key design parameters and the influence of constraints on them (*e.g. What is the influence of restricting the depth of the structure on the bottom flange area of a spine beam bridge?*).

2. Investigation of the possibility of developing design algorithms for the automated determination of key design parameters. The authors firmly believe that one overriding criterion should be:- *Anything which can be calculated, should be calculated.* Procedures such as those dealing with methods of determining concordant profiles which satisfy certain design constraints[9] in the case of prestressed concrete beams can be incorporated into expert systems.

3. Selection of key design parameters with adequate provision to cater for unforeseen or overlooked constraints and complexities, and also for those aspects which cannot yet be calculated. These would include:-
    - *Selection of prestress force and eccentricity so that typical construction tolerances in duct placing or jacking do not give unacceptable stresses in the beam.*
    - *Selection of section dimensions with adequate provision for a subsequent check on temperature stresses.*
    - *Provision for redistribution of forces due to long term creep effects.*

4. Explicit identification of the various aspects which govern each of the design parameters, e.g.:-
    - *Top flange thickness governed by tranaverse flexure of the top slab.*
    - *Bottom flange area governed by overall bending effects.*

5. Development of techniques which can take account of the governing behaviour quantitatively, thus effectively reducing the number of heuristic rules to be incorporated into the expert system. Thus, work such as that by Low[10] and Burgoyne[9] on the determination of minimum prestressing forces, gives specific rules for the minimum (and maximum) prestressing force which is required in a given beam, thus doing away with rules of thumb which are otherwise needed.

With such methods, it should be possible to satisfy the ultimate goal of producing an expert system which can produce preliminary designs comparable to a human expert.

Detailed design

In the detailed design phase, the full cross-section shape is chosen, including all splays, kerbs, drainage details and so on. Similarly, individual prestressing cable profiles are chosen (rather than just the centroid of the cable profile), and reinforcement is specified. At this stage most code of practice checks are performed, other than those which are likely to govern section dimensions, which have been taken into account at an earlier stage.

Design documentation

Design documentation would include the equivalents of current design calculations, for example showing that the applied bending moment was everywhere less than the sections moment of resistance, but it could also include much more information about why a particular design was chosen.

Expert systems should also be capable of linking to CAD packages, to produce drawings to justify the design (such as bending moment diagrams), but also to produce detailed construction drawings.

FAILURE OF DESIGN CHECKS - REDESIGN

A problem that occurs in expert systems for design is associated with what happens when a test fails. Checks against code rules are very often undertaken at a late stage in the design process. For example, it is common to check shear strength and deflection criteria after the basic cross-secion has been determined. These will normally be checked in the expectation that the criteria will be satisfied, but if the test fails, where does the expert system go back to in the design process? Failure leads to modification at the detailed design stage, referred to in expert systems jargon as redesign. Redesign becomes a complex task due to the number of options available to a designer. It normally consists of two stages.

1. Identification of the options available for redesign in a particular situation.

2. Implementing one or more of the options available to rectify the failure.

According to Boyle[11], options available for redesign are the following.

1. Modifying one or more of the parameters of the design generated.
   - *e.g. If shear resistance is inadequate, we note that shear resistance depends on web area, web reinforcement, and the contribution from the prestressing cable, but we must note that there are complexities which arise, such as the effect of changing web area on the flexural behaviour, and the (usually narrow) bands within which the cable must lie.*

2. Investigating alternative design operations that are possible.
   - *e.g. Introduce vertical prestressing in the webs.*

3. Modifying one or more of the current design objectives
   - *e.g. Allow the web thickness to vary locally.*

4. Deciding that the failure is so severe that this design option must be abandoned and a completely different alternative sought. This is clearly a very difficult decision to justify.

The strategy employed to identify the decisions required for redesign is the knowledge of dependencies. Expert systems use dependency directed backtracking to establish dependencies. However, as pointed out by Mittal & Araya[12], the shallow knowledge included in heuristics is of little value in deciding which way to modify the design. For example, knowledge that the shear resistance depends on the web area does not tell us by how much we should change the web area, since there are consequential effects of increased dead weight moments, and increased prestress.

In order to overcome the complexity of redesign decisions, Kumar & Topping[13] have produced trees of dependency networks (Fig. 2). This approach is still in its infancy.

The complexity involved in redesign has been responsible for the failure of expert systems to address redesign properly. Hence, they have not found wide acceptance yet

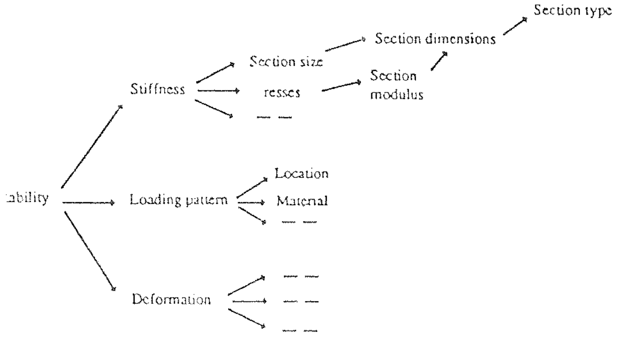

FIG.2 A PORTION OF A DEPENDENCY NETWORK (FROM KUMAR & TOPPING [13])

industrial applications. This emphasizes the need to produce better preliminary solutions which need the least amount of modifications in the detailed design stage, thus minimizing the need for redesign.

DEEP KNOWLEDGE FOR PRELIMINARY DESIGN

As described earlier, the success of the expert systems for preliminary design depends on their ability to generate preliminary solutions which have a best chance of succeeding at the detailed design stage. The type of design rules which should be included to achieve this goal can be categorized according to the level of complexity.

Some of the rules are common sense. Consider a rule for the width of the top flange of a road bridge.

- The top flange width in metres must be *(width of the each traffic lane)*

* *(No. of traffic lanes) + (central reservation width (if one exists)) + (pavement width (if needed)) + 2.0m (to allow for kerbs and handrails).*

Others may be taken from rules of thumb that govern practicalities, such as difficulty of placing concrete.

- *If the bridge is to be built by in-situ construction, then the web thickness must be not less than 0.25m if the web contains one prestressing duct, or not less than 0.35m if the web contains two prestressing ducts.*

But these may be replaced by more carefully worked out rules, such as one given by Guyon [14], which considers the requirements of construction directly (Fig. 3):

- *If the web depth (h) is less than 6 metres, then the web thickness (a) must satisfy* $\{a \geq h/36 + 50 + \phi\}$ *where* ϕ *is the diameter of the cable duct.*

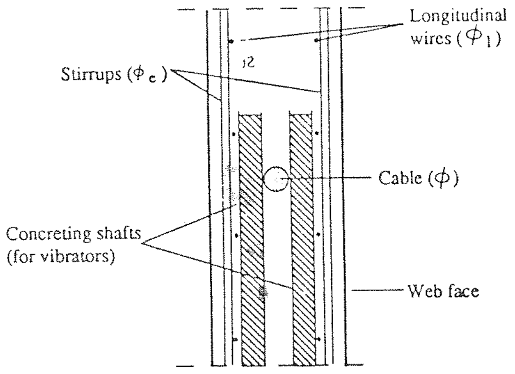

FIG.3 MIMIMUM THICKNESS OF WEB

Other rules may be derived from code requirements, which avoid the necessity for detailed calculations.

- *For cantilevers the span/depth ratio must be less than 7.*

but this can be replaced by a rule which is more difficult to apply, but which is usually less onerous, in that it will allow thinner sections provided a more detailed calculation is carried out.

- *The deflection at the tip of a cantilever shall not exceed span/200.*

These are the common types of rules used in majority of the expert systems for the preliminary design. However, these alone are not sufficient to produce good preliminary solutions which succeed at the detailed design stage. If an example is considered from the design of prestressed concrete spine beams, the main design parameters selected at the preliminary stage consist of:

1. section dimensions
2. the cable force distribution
3. the cable layout.

Each of these are briefly described to highlight the complexity which the designer faces when selecting these design parameters and also to emphasize the difficulty of incorporating this knowledge as heuristics, without obtaining a fundamental understanding of the design principles.

Selection of section dimensions

The section dimensions that should be used depend on the following aspects:

1. The cross section and longitudinal section layout of the structure (eg: span, type of supports, skew, no. of webs)
2. The loads acting on the structure.
3. The magnitudes of the secondary moments due to prestressing forces.
4. The method and sequence of the construction and the stressing of cables.
5. The effect of long term creep on the structure.
6. The temperature stresses which depend on the shape and location of the bridge.
7. The effects due to structural phenomena such as shear lag.

These illustrate the amount of complexity that can be involved in the selection of the cross sectional layout since most of these effects can be unique to a particular bridge (eg: cross and longitudinal layout, secondary moments, construction sequence).

A question can be raised; *'Is it possible to draw general design rules when the structures designed are unique?'*

This clearly highlights the need to develop design algorithms which can use the numerical power of the computer to generate design parameters such that they either take account of the above constraints or make sufficient allowance for them. Perhaps surprisingly, these design algorithms are not available, and so need to be developed. This requires the undertaking of a detailed study into the design process itself in order to unravel the principles behind the expert's reasoning. Once this is achieved, the mysterious perceived wisdom of human experts could be taught to novice designers as engineering design and also be included in expert systems. A detailed account of the way that this is achieved for the preliminary design of prestressed concrete spine beams is described by Jayasinghe[15].

An example can be taken from the same domain to illustrate that certain design concepts can be used in a slightly unconventional way to derive the design parameters. Consider the design of a prestressed concrete cross-section shape. The section has to be capable of being prestressed; that is, for the loadings that are applied to the structure, a feasible combination of prestressing force and eccentricity must exist. Most good designers of prestressed concrete are familiar with the idea of a Magnel diagram, which plots the eccentricity of the cable against the inverse of the prestress force; stress limits then appear as straight bound lines (Fig. 4). Designers usually use this diagram to design the prestress itself. However, the bound lines must define a feasible combination of force and eccentricity which not only exists, but which also satisfies some practical constraints, such as that the eccentricity lies within the beam when the primary and secondary moments act on the section.

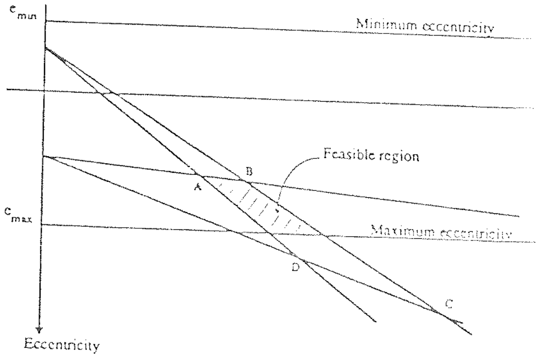

FIG.4 TYPICAL MAGNEL DIAGRAM

However, we can make much more use of the Magnel diagram. The requirements on the existence of a valid Magnel diagram can be translated into limits on section shape, most particularly in the form of minimum areas of the top and bottom flanges. Other conditions, such as the practical ones given above, and limits on the ultimate strength capacity of the section, also put limits on flange sizes. These calculations are tedious to perform by hand, and are therefore rarely performed by human designers explicitly. Derivation of these conditions requires logical consideration away from the design process itself. But once the rules have been found, they can be used to determine section dimensions in place of the rules of thumb used by most designers.

Selection of the cable force distribution

In a continuous structure, the cable force may differ between spans and also within each span. The selection of upper and lower limits on the cable force at each cross section is a trivial task since the Magnel diagram can be used directly. The difficulty is the selection of cable forces so that the previously assumed magnitudes of the secondary moments can be obtained at each support. If a sufficiently large cable force is not selected, then the designer will have to resort to design by repeated analysis, but will never reach a satisfactory solution since none exists.

The selection of cable forces to satisfy a number of different scenarios are discussed by Low[10] and later generalized by Burgoyne[9]. These methods are developed from the viewpoint of dsign, so that the design parameters, or limits on them, are determined such that subsequent calculations are satisfactory.

Selection of cable layout

An automated iterative procedure has been introduced by Burgoyne[16]. The iteration will be successful only if legitimate cable forces are selected so that a feasible cable profile exists. This further reinforces the idea that preliminary solutions cannot be solely based on heuristics, but should be based on design algorithms which can delve into the underlying fundamental design principles.

These examples illustrate a central tenet of what we believe a good expert system will do. Those things which are amenable to calculation should be calculated. Heuristics should only be used for those things which cannot be calculated, or for which no calculation procedure has yet been defined. By taking time to develop better rules or better procedures than those used by most designers, the expert system will in most cases match the expertiese of individual experts, and in some cases will exceed the capabilities of any one expert. This level of expertise will only be achievable when written by someone capable of delving deeper into the subject.

These complex rules, which are often known as *metarules* in expert systems jargon, are fundamental to the behaviour of the expert system. They cover such things as the effect of the interaction of one parameter on another. Knowledge of them is very difficult to obtain, and they are the aspects of the design process which leads to it being called a *'black art'* by many people. An understanding of these rules is often regarded as being the mark of an experienced designer.

The design algorithms that will be included could be numerically intensive. Hence, expert systems for preliminary design should be coupled systems so that they are capable of handling declarative knowledge and procedural routines. Since the algorithms encapsulate the fundamental engineering principles, they are a prerequisite for developing deeply coupled expert systems.

CONCLUSIONS

Systems, that deserve the title *expert,* need to go back to 'first principles'. Simply entering code of practice rules into a database does not produce an expert system; attempts to do this have produced systems which most engineers regard as trivial. Reasoning from first principles should lead to a considerable change in the way we think about structural behaviour in general and design in particular. This will reflect the changes that took place in analysis twenty year ago.

Structural analysis text books written prior to 1960 concentrated on techniques for minimizing the number of equations to be solved. The reason for this is not hard to see; solution of more than about 5 simultaneous equations by hand was time-comsuming and so prone to error that it was not worth doing. Relaxation methods were better, especially if self-correcting, but no methods were entirely satisfactory.

When computers came to be regarded as sensible tools, the solution of large numbers of equations ceased to be a problem, so more complex structures could be analysed. A more important result, however, was the fact that structural analysis itself became rationalized. Consistent matrix methods, such as stiffness and flexibility methods are now the way the subject is taught.

We believe that a similar change will take place in design. The ability to store rules in the form ''If A then B'', means that it has become worthwhile studying the design process with a view to incorporating it into expert systems at some stage in the future. What is required at this stage is a study of the fundamentals of the design process to get the knowledge into the most suitable form.

We do not believe that the currently available expert systems will be seriously used for design as they stand. Instead, they will be used as test beds for various aspects of the design philosophy. We expect that the current work will lead to publication of design principles, in plain English, not as rules in Prolog or other expert system languages. This will lead to the identification of and the rationalization of conflicts between experts, as indicated earlier. For the first time, it will be possible to have texts about the design of structures which actually refer to that subject, rather than merely to analysis. Better understanding of the design process will lead to better teaching both to undergraduates intending to become engineers, and also to those engineers already in practice who wish to get a better understanding of the underlying principles.

True design expert systems are a long way ahead, but we believe that they are a goal worth working towards because of the way they will assist us to understand the design process itself.

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