DESIGN OF PRESTRESSED CONCRETE BEAMS USING EXPERT SYSTEMS

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The design of prestressed concrete beams is arguably one of the most complex tasks facing the structural engineer. With most materials, the designer has to choose the shape of the cross section; in many cases this means the choice of web and flange thicknesses for one of a restricted range of standard cross-section shapes.

In prestressed concrete, there are more unknowns. Not only is the shape variable, but the amount and position of the prestress can be varied to suit the particular application. Even the selection of the section shape is more complex, since the use of concrete allows the use of non-prismatic sections, with tapered flanges and webs, more easily than with steel sections.

If the structure is statically indeterminate, the designer must consider the effects of parasitic (or secondary) moments set up by the action of the prestressing force. The shape of the cable profile along the whole length of the beam (which controls the parasitic moments) must be taken into account when designing each cross-section.

In the hands of an expert designer, these compexities can appear no more than minor irritations, and indeed, can be turned to advantage. For example, the double-T section shown in Figure 1 is widely used by one UK consultant for continuous road bridges. Similar sections are frequently used for simply supported floor beams, since they have a large top flange, which gives adequate compressive strength in sagging bending, when the prestressing tendons can be placed at the bottom of the webs. But how can such sections work over the piers in viaducts, when the structure is subjected to hogging moments? The cables can be placed at the top of the structure, but what is carrying the compressive stresses, since there is no bottom flange?

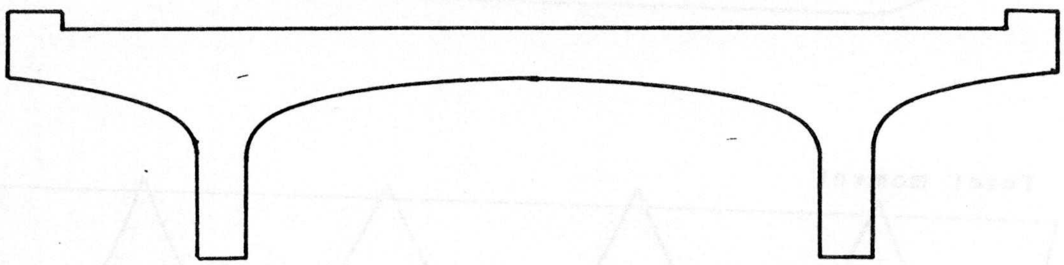

Figure 1. Double-T section for continuous bridges.

The answer is that the designer deliberately chooses a cable profile which will give a parasitic moment that is sagging everywhere. This reduces the hogging moments, which the structure cannot carry efficiently, and increases the sagging moments, which it is very good at carrying (Figure 2). This allows efficient use of the section, which is easy to build because there is no internal formwork and the section can be poured in one go, and avoids the problems associated with having joints between spans at every pier, with all the attendant maintenance problems.

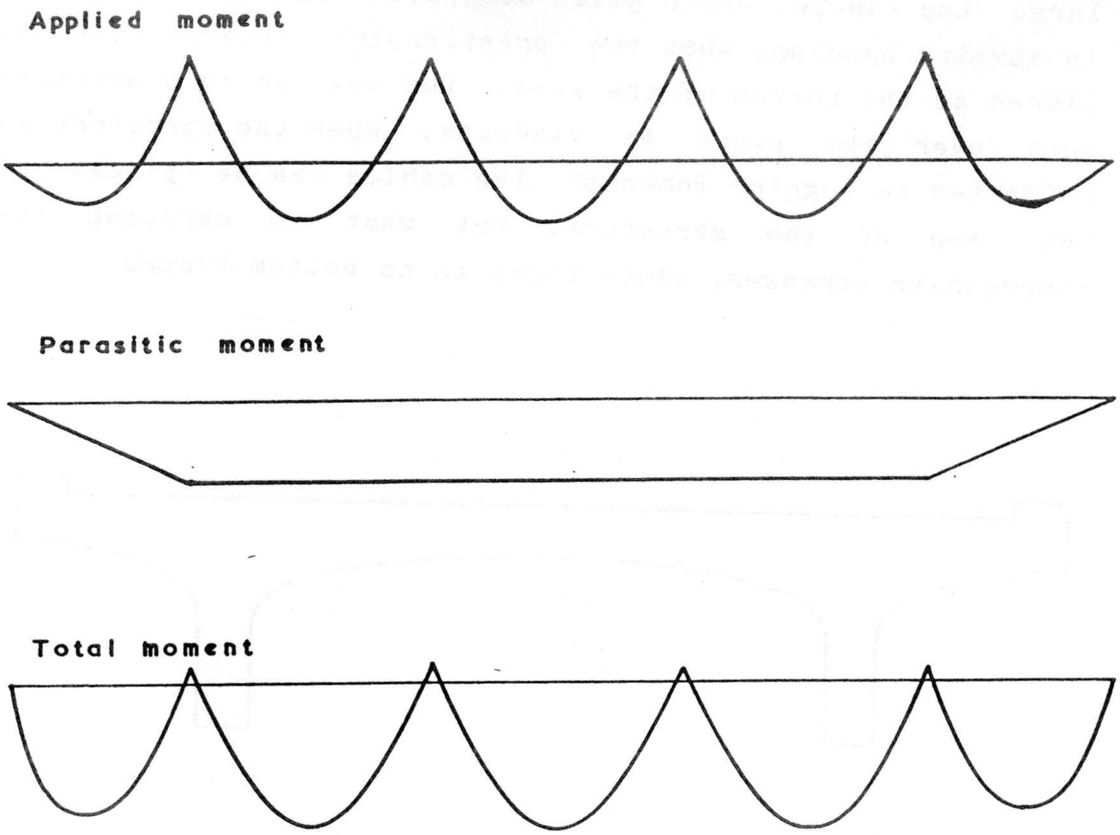

Figure 2. Use of parasitic moments to reduce hogging.

Thus, prestressed concrete offers an exciting challenge to the builders of expert systems. There are considerable potential benefits, in that the number of designers who use the material to its full extent is quite small, despite the large number of prestressed structures around. There are many technical papers published about prestressed concrete, but most are concerned with how to analyse the structures, or discuss the design of individual structures, rather than referring to design as a general procedure. Additionally, there are long established arguments about the best way to consider prestressed concrete, which are sometimes almost theological in their intensity.

It is against this background that the work outlined in this paper is being carried out. We are not attempting to apply Expert Systems to a trivial problem, for which flow charts and design manuals already exist; rather, we note that the principles of Knowledge Engineering in general, and Expert Systems in particular, offer to the structural designer the same potential for revolutionary change that occured in the world of the structural analyst 25 years ago with the advent of FORTRAN, matrix methods and the resulting simplifications in numerical computation.

The ramifications of that quiet revolution are still being felt. Until the early 1960s, the constraint on analysis was the difficulty of solving a large set of simultaneous equations. Many of the established techniques of structural analysis were designed to minimise the number of equations to be solved, and these techniques are still in widespread use by older engineers, and are still being taught to undergraduates, despite the fact that they are no longer the best.

The first stage of our research is thus to break design down into its constituent parts, and to study the most appropriate ways of making use of knowledged based systems. At the same time, this approach throws up the gaps in existing human knowledge, and the conflicts that exist between the experts.

Design of prestressed concrete

Early attempts at automating the design process for prestressed concrete were based on numerical optimisation techniques, in which the controlling variables of the structure, such as number of webs, web and flange sizes, and cable profiles, were varied by small amounts until an 'optimum' structure was achieved. The number of structural analyses performed was enormous, up to 200 being quoted in one example [1], which is 'design by repeated analysis' taken to an illogical conclusion.

Figure 3, which is taken from reference [2], shows our first attempt at rationalising the design process for prestressed concrete bridges. The solid boxes each relate to one stage of the design process. In most cases, they are well established procedures which are written up in many texts. It is the interaction between them which forms the basis of our study.

The elements within dashed boxes are those areas which have been identified as most appropriate for expert systems.

Expert system for preliminary design

The first stage of the design process is conceptual. The designer has to make certain decisions, most of which do not involve complex numerical calculations. The designer must select the layout of the spans, and the method of construction, which can have a large impact on the rest of the design. For example, an incrementally launched structure requires a prismatic section and an alignment that is either straight both vertically or horizontally, or else has constant curvature. A balanced cantilever approach often benefits from non-prismatic sections, but has specific constraints on the spans to minimise the amount of temporary

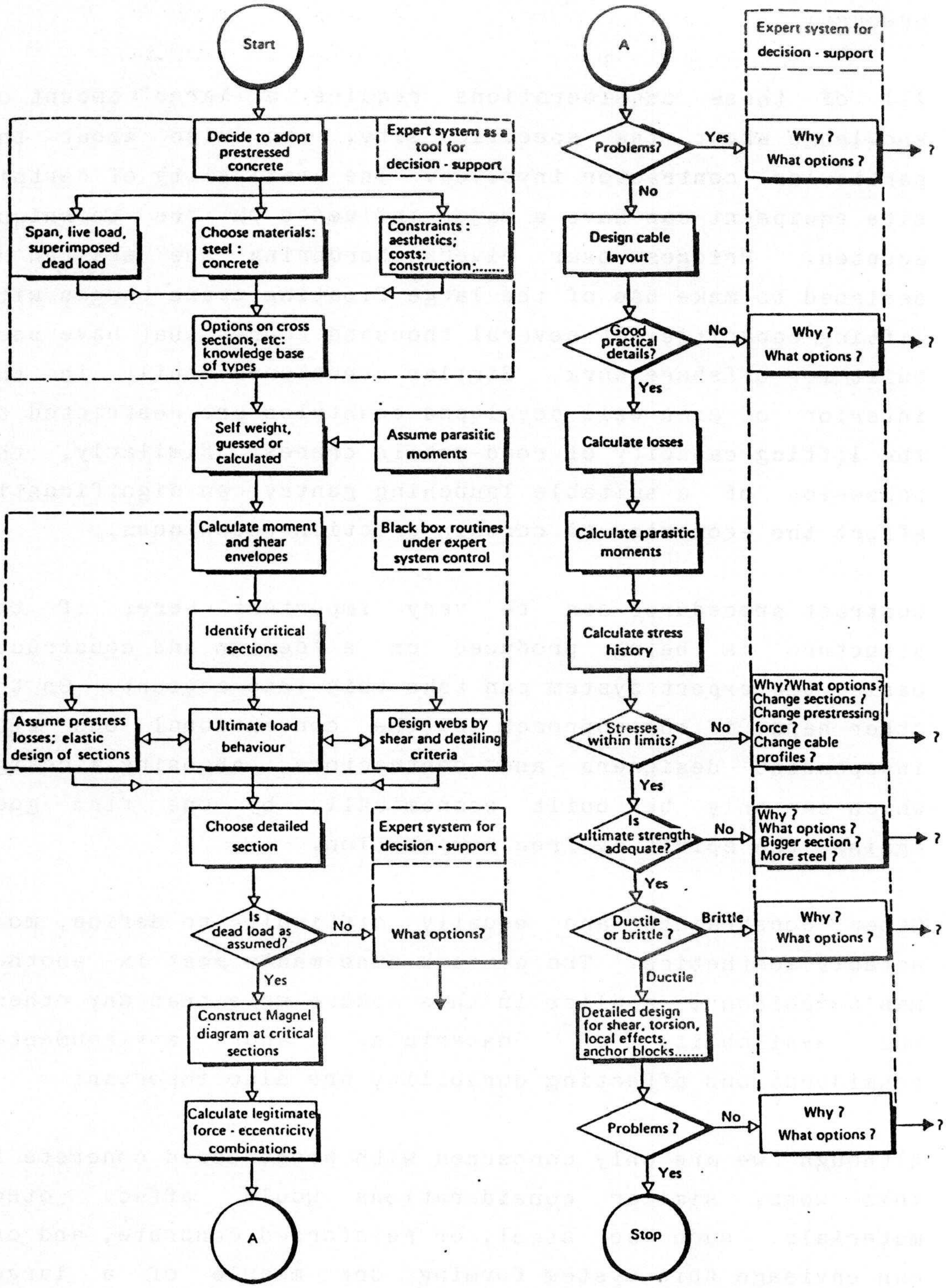

Figure 3. Design procedure for prestressed concrete

propping that is required. Decisions must also be made on as to whether the structure is to be built in-situ, or precast.

All of these considerations require a large amount of knowledge about the specific site, and also about the particular contractor involved. The availablity of certain site equipment can have a major influence on the technique adopted. Bridges over rivers bordering the sea can be designed to make use of the large floating crane barges with lifting capacities of several thousand tonnes that have been built for offshore work. Similar structures built in the interior of even well developed countries are restricted to the lifting capacity of road-mobile cranes. Similarly, the possesion of a suitable launching gantry can significantly affect the economics of certain erection techniques.

Contract procedures can be very important here; if the structure is being produced on a 'design and construct' basis, the expert system can take this into account. On the other hand, if the approach is the conventional one with independent designers and contractors, choosing a design which can only be built economically by one firm goes against the spirit of free competition.

Other constraints are equally difficult to define, most notably aesthetics. The proverb "One man's meat is another man's poison", applies in this sphere more than any other. The availablity of materials, and environmental considerations affecting durability are also important.

Although we are only concerned with prestressed concrete in this work, similar considerations would affect other materials, such as steel, or reinforced concrete, and one can envisage this system forming one module of a larger expert system, which would allow the best design to be selected from a wide range of alternative materials and forms.

This phase of the design process, though complicated, can be implemented quite easily; the rules are primarily concerned with facts which can be represented in a straight-forward manner in Prolog or an expert system shell. Work is currently underway interviewing practising engineers and producing a core system to perform this work.

Expert system to control numerical routines

The next stage of the design process requires interaction between numerical calculations and decision making. Typically, the human designer alternates between decision making and computation until the design is complete. As far as possible, simple calculations are carried out first, to fix the main parameters, since these may have to be repeated if the design fails. More complicated calculations are carried out at the end, by which time the engineer is reasonably certain that the design will succeed.

The numerical calculations are best performed by compiled and optimised routines written in algorithmic languages, such as FORTRAN or PASCAL. For example, the calculation of the ultimate moment capacity requires an iterative calculation in which the strain distribution is varied until equilibrium is satisfied. The calculations for the moment and shear envelopes require calculations on influence lines obtained by structural analyses carried out at many positions within the beam.

There is no reason why these routines should be re-written in declarative languages to fit in with the knowledge engineering approach. Instead we should concentrate on the use of expert systems to control these routines. There is real scope for research in this area, but there are many potential pitfalls, since there are many ways of viewing structural design philosophy.

Let us take, as an example, the processes adopted to choose the shape of the cross section of the structure. Designers of prestressed concrete can be divided into three distinct schools. There are those who may be called the French school [3], who derive their ideas from Freyssinet, who believed that concrete should be prestressed to eliminate, or at least reduce, the tensile stresses in a beam. Others adopt the German approach [4], sometimes ascribed to Dischinger, that prestressed concrete should be viewed as a way of prestraining very high tensile steel so that its strength can be utilised at strains that the structure can accomodate without obvious signs of distress. Yet others adopt the American approach (due to Lin) [5], and choose a cable profile that balances one applied load, to eliminate deflections for that condition.

We may characterise these three philosophies as 'stress design', 'strength design' and 'deflection design' respectively. Exponents of each system will, nowadays at least, acknowledge that the other points should be taken into account, but they are convinced that their own ideas are 'more fundamental'.

How can an Expert System be written to cope with these three viewpoints? This is the sort of question that cannot be answered by outside systems analysts, who are struggling to understand the subject, but only by domain experts who are familiar with the requirements of expert systems. In this case, an answer can be provided by noting that the load balancing approach can only be used to balance one applied load, and the strength approach can, at best, only provide information about the size of the compression flange of the beam, the size of the prestressing tendon required, and the distance between them. Thus, these two techniques can be best used as guidance for preliminary design, followed by detailed design using the stress criteria. Such an approach has been found by the author to be a reasonable one which reconciles the apparently conflicting views of the various schools.

Calculations not under expert system control

At a later stage in the design process, much of the procedure can be left entirely in the hands of straightforward numerical calculations, with only the minimum supervisory control from the expert system.

Once the section profile has been chosen, the allowable combinations of prestressing force and eccentricity can be calculated at all points along the length of the beam. This is an entirely mechanical process.

Similarly, the calculations for the parasitic (or secondary) moments associated with the chosen cable profiles are also purely mechanical, although the intermediate stage, in which the actual cable layout is chosen, may well be done by the declarative, knowledge-based, part of the system.

Recent developments in understanding of the problems associated with cables in statically indeterminate beams illustrate the effect that computers have had on the design proces, and point the way to future changes that can be anticipated when a thorough comprehension of experts systems is more widely known.

In indeterminate structures, the cables can induce parasitic moments because the tendency of the beam to deflect under the action of the cable loads is resisted by the indeterminacy of the supports. These moments have to be regarded as loads, and so should be taken into account at an early stage of the design process. However, they cannot be calculated until the cable profiles are known, which is one of the last stages of the design process; what is worse for many designers, they have to be calculated by fairly tedious calculations and the solution of simultaneous equations. The literature up until the early 1970s is full of papers giving methods of calculating these moments, with the aim of reducing the complexity of calculation to the minimum. The onset of computers solved that particular problem, so the calculation itself became of no real significance, and apart from papers describing how the calculations were performed on different computers, the literature dried up.

More recently however, we see a new phenomenon arising. Engineers who can easily calculate the parasitic moments, are starting to become interested in the design, as opposed to the analysis, side of the problem. Thus, we see papers looking at constraints on the design of cable profiles, which, if taken into account at the preliminary design stage, will allow simple calculations subsequently of the detailed profile. Such ideas can be presented by designers [6], who have come across solutions when facing practical problems, but they are often followed up by academics who refine and generalise the principles [7].

We thus see a change, away from studies of analysis problems, which were largely resolved by the ability to solve large sets of simultaneous equations, towards studies of design problems.

Expert system to check design calculations

As the design progresses, more parameters become fixed, and it is possible to carry out checks on the design process.

For example, once the cross-section has been designed, it is possible to calculate the actual dead load of the structure, and compare it with the value that had been assumed at an earlier stage in the design process.

Similarly, once the detailed design of the prestressing cables and any untensioned reinforcement is complete, it is possible to check that the structure has adequate strength and ductility.

In many cases, the result of these checks will be confirmation that the design is adequate. But what happens if the check fails? Clearly, some earlier decision is wrong, and must be reformulated, but which one?

Let us suppose that the dead weight is wrong. What are the options? If the error in the dead weight is small, it may be possible to show that the stresses nevertheless remain within acceptable bounds, so no further action is required. If the error is a little larger, it may be sufficient to move the prestressing cables a little, at one or more locations. If the variation in dead weight is large, we may have to redesign the section.

There may be differences in the action we take depending on whether the dead load was over- or under-estimated. For many structural materials, an over-estimate may simply mean that the structure is more conservatively designed (but less economic), whereas an underestimate may mean that it is unsafe. For prestressed concrete, both may be structurally significant, since the dead load is required to partially balance prestressing forces. If the dead load is less than assumed, the structure may fail as soon as the prestress is applied.

Thus, the writer of an expert system must decide what to do in all these cases. Design guides, in so far as they exist already, do not address these problems directly. Flow charts for design include such elements as 'Check that the dead load is as assumed', with an arrow going on to the next stage if the check succeeds, but with no indication as to what to do if it fails. The implication is that the engineers will use their judgement to decide what to do next, and it is this judgement that must be encapsulated in the expert system.

The problem can be simplified, though probably not avoided, if rational estimates can be made at an early stage in the design process. Thus, the better the initial estimate that can be made about the dead weight, the more likely it is that only minor changes will be necessary if the dead weight check fails. It thus becomes desirable to establish data bases of structural forms that have been found acceptable. If these are accomodated within the expert system, with suitable intelligent interrogation rules (since it is unlikely that any particular structure will correspond precisely to one that already exists), then logical decisions can be made at an early stage in the design process. However, one must be careful to ensure that the errors of the past are not perpetuated. Simply because a lot of structures have been built in one particular way does not mean that this is the best way of doing things, but it should indicate that a given starting point will lead to a feasible design.

Care is also needed when considering intelligent systems that can learn as they go along. An initial data base will presumably be set up to form a core from which early decisions are made. However, as time progresses, and the system adds extra solutions of its own, the new designs will start to overwhelm the old designs. But are the new designs valid? They may have passed all the tests included by the builder of the system, but do they also pass the ultimate test, that of acceptance by a client in competition with designs produced conventionally, or by other expert systems? Perhaps only designs which pass this more stringent test should be 'learnt' by the data base. Designs which the system has produced, but have not yet been accepted externally, could be flagged to indicate their status, given a lower weighting when considering the implications for subsequent designs, and be removed from the system after a while if they do not pass more rigorous tests.

Another way of minimising problems associated with an earlier, erroneous, decision is to give that decision error bounds. Thus, instead of estimating the dead load as, say, 150kN/m, it would be better to estimate that the dead load was in the range 140kN/m - 160kN/m. The calculations become slightly more complicated when upper and lower limits have to be taken into account, but that is, after all, what computers are good at.

Sources of rules

The rules in an expert system will be derived from many sources, and may differ between different versions of the expert system used in different countries, or between different firms.

Some will represent scientific fact, and so will remain the same in all versions of the system.

Some will be based on the requirements of the country or state where the structure is being designed (such as the loading requirements), but are not likely to differ between individual firms.

Others may vary depending on who will build the structure, since some designs may be affected by the availability of specialist equipment, or may reflect the skills of a particular company.

Yet other rules may reflect the prejudice of the designer himself, and will only be present in a system built around his knowledge.

Because expert systems can be built from rules that can be supplied in any order, it will be possible to tailor make the system to suit particular requirements. By making use of expert system shells to handle the interaction with the user, it will be possible to have a core of routines in one language, but with rules in the shell which communicate with the user in another language. Thus, it will be possible to have the standard scientific module, combined with a company's own module, with the module for a particular code and communication with the user in his own language. This will give great flexibility to properly written systems, which will be important if such packages are to become widely accepted.

Conflicts between experts

The development of an expert system for design is highlighting problems associated with conflicts between experts.

This is a problem which has not been given the attention it deserves in the past. There seems to be a commonly held belief amongst computer scientists that in the domains where expert systems will be used there is an agreed standard of what is correct, at least among true experts. It is implicit in this viewpoint that the existing human experts are right and that the problem is one solely of extracting the information from them.

However, to scientists and engineers within any given domain (not just prestressed concrete), things are not so simple. We all know engineers whose judgement we would not trust, and we know engineers who are world experts in one field, but have only a passing knowledge of others. Such poblems can be resolved fairly easily; we do not take advice from the former, and we only take advice in one area from the latter.

More serious is the problem that arises when two experts hold mutually exclusive, but independently defensible, views about the correct way to do something. They may both be capable of designing structures that would satisfy the constraints, but which work in entirely different ways.

The builder of an expert system is faced with a dilemma. Both sets of knowledge can be incorporated in the rule base, so that the system will try to provide valid solutions using both sets of rules, but we are then faced with the problem that some of the rules may conflict.

The worst scenario of all is that one of the experts is right, and the other wrong, but the arguments that both use to defend their theories are superficially valid.

For all these reasons, the builders of the expert system must themselves be, or become, experts in the domain itself. The conflicts between experts must be identified, and resolved, prior to incorporating the information in the system.

One corollary of this argument is the need to carry out more directed studies within the domain, before setting out to produce the system. In the past, 'design studies' have been the poor relations amongst research programmes, when compared with the effort put into, say, finite element analysis. That situation must be reversed. We know how to analyse virtually any structure, and with the onset of cheaper computers, that power is available to most engineers.

What we do not know is how to do design, other than by the traditional method of 'design by repeated analysis'. However, the fact that tools are now appearing which will allow us to represent knowledge, means that it becomes worthwhile to go out and look for that knowledge. Until the advent of knowledge based systems, such information could not be recorded in a form usable by computers.

In order that this information gathering process can proceed effectively, it is important that those from whom the information will be gathered are made aware of the potential benefits of such systems, so in-service training of practising engineers in this field is essential.

Conclusion

Expert systems will make a major impact on design. The fact that knowledge can be represented in a form usable by machines will mean that it is worthwhile gathering the information in a standard form.

The requirement for codifying knowledge will lead to an identification of the conflicts between experts, and in order to resolve those conflicts, research will be necessary in the domain before attempts are made to encapsulate the knowledge.

This work will, of necessity, be carried out by domain experts themselves, since they are the only people who will be able to appreciate the subtleties of the arguments raised in the conflicts.

Expert systems will lead, not just to an automated form of human design, but to a revolution in the way design is carried out, akin to the revolution that took place in analysis when digital computers and procedural languages were introduced.

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