Expert Systems for Structural Design – Not yet the whole solution

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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 rationalisation of analysis procedures in the 1960s.

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

We start with two definitions.

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 dimensions 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 structures, design involves the selection among a large array of possibilities of many particulars, such as structural layout, the shape of a member, the*

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.

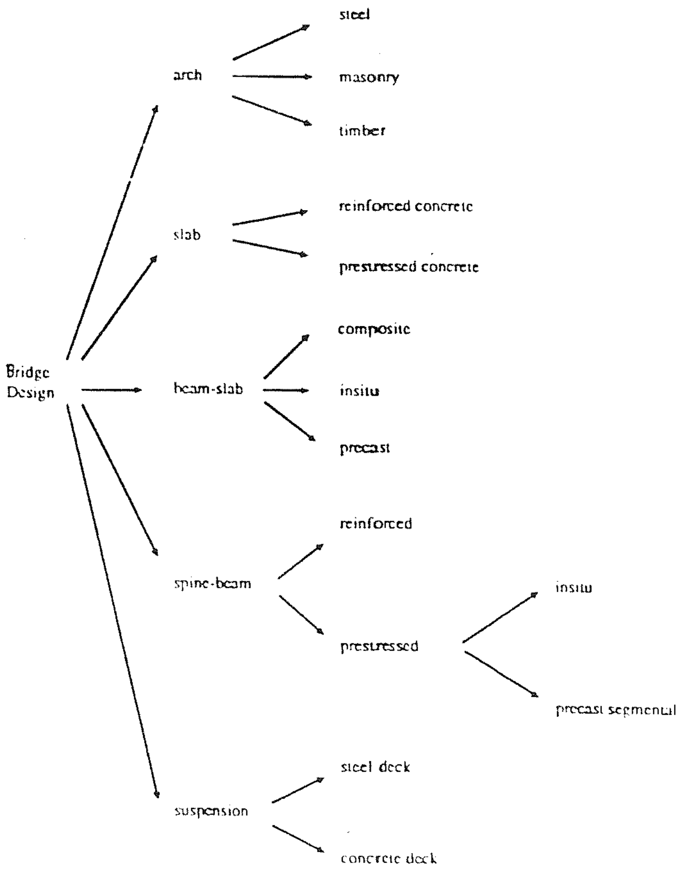

Figure 1. Hierarchical decomposition based on bridge type.

Design can be regarded as hierarchical, and different designers can represent the hierarchy in different ways. Thus, we can think of bridges in terms of the form of construction (Figure 1), with materials as a subsidiary aspect, or with the material as the most significant subdivision (Figure 2). This leads to different sorts of expert systems; Sham [3]

Those relating to national or local conditions would cover such things as the differences between the ranges of standard sections available in each country; the differences in size of sections that can be transported on the roads, or the availability of certain materials, such as light-weight aggregates. The national rules might also reflect code rules, such as limits on the articulation of the structure or the provision of earthquake resistance; on the whole, however, an expert system that covers conceptual design should not need to make many references to codes of practice, unless the codes themselves impose governing criteria that cannot be justified on engineering grounds alone.

The rules covering practical considerations are in many ways the simplest to produce. For each type of bridge structure they would cover the conditions that have to be satisfied before that option can be considered. Thus,

> *Incrementally launched bridges must have decks that are either straight or part of a circular curve.*
>
> *Balanced cantilever bridges have to satisfy certain conditions on the sizes of adjacent spans.*
>
> *If the bridge is built of in-situ concrete, site access must be available over a significant proportion of the length of the bridge.*

These rules can be provided by experts, but they can also be derived from common-sense arguments. A study of recently built bridges would yield these rules, without much knowledge of the underlying behaviour of structural mechanics; they could therefore be drawn up by a 'knowledge engineer' who is not a specialist in the field.

The rules based on an engineer's judgement are the most complex, and the ones that are dependent on a deeper knowledge of the subject. They will vary from expert to expert, and it is unlikely that there is any one set of rules that can be regarded as correct. For example, in the field of concrete bridge design it is well established that in-situ reinforced concrete is cheaper for short spans, but that precast prestressed concrete becomes more economic at larger spans. One expert might say that the change over point is at a span of 15m, while another might say that it occurs at 20m. A third might say that it occurs at 18m in normal conditions, but at 12m if there are difficulties in providing access for falsework to support the shuttering. The elicitation of such rules from 'experts' is not a trivial matter. Early proponents of expert systems suggested that a non-expert could elicit the information by interviewing acknowledged authorities, and it is true that a certain amount of information can be obtained in this way. Systems produced in this way tended 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.

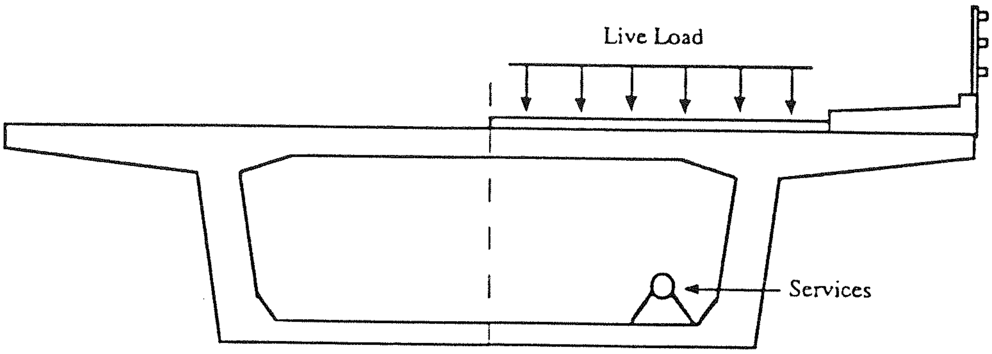

Figure 3. Typical spine beam cross section.

This phase of the design process is one where major contributions from expert systems can be expected, but only after detailed study of the problems by structural experts themselves. Studies of the preliminary design phase should be carried under the following topics.

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.* Thus, papers such as those dealing with methods of determining concordant profiles which satisfy certain design constraints (Burgoyne [5]), give procedures which 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.

arrangements. To the human detailer, it may be obvious which bar should be moved, or if a different bar layout is possible, but to try to extract that information and codify it as a set of fool-proof rules will be very difficult.

In this context, it is instructive watching first year undergraduates coming to grips with attempts to detail a simple reinforced concrete beam. The interaction between bar size and effective depth, within a given beam depth, can be confusing, as can making allowances for grouped bars and lapped bars.

DESIGN DOCUMENTATION

Most expert system languages give the possibility of justifying their decisions, by means of such statements as:-

> *I can show that ..... because I have a rule which states ..... and I can show that the necessary conditions are satisfied by ......*

In essence the problem is being broken down into a series of goals. In order to show that one goal is satisfied, it may be necessary to show that subsidiary goals are satisfied. Each of these can be treated in the same way, leading to a heirarchy of design decisions, and justifications for them, which can be printed out to give the design documentation.

This 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.

The extent to which a firm using an expert system would want that information published in contract documents, for example, is a question that remains to be tackled. In the same way, the question of who owns the expertise in the system (the author of the system, the original expert(s), or the firm that has purchased a copy of the expert system) and who is responsible for a design carried out by the system are areas which will keep lawyers busy for years. The same difficulties arise with conventional analysis programs, and in expert systems, which essentially incorporate analysis packages, the problems will be worse.

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.

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, 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 [8] (Figure 4):-

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

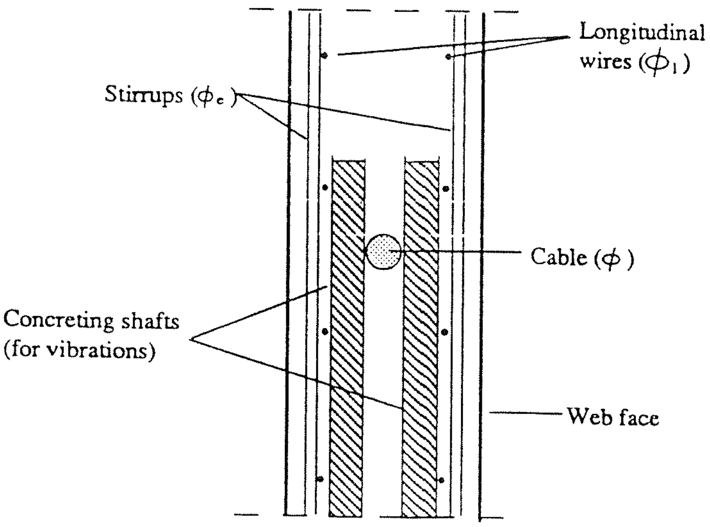

Figure 4. Minimum thickness of web.

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.

ultimate strength capacity of the section, also put limits on flange sizes. These calculations are slightly tedious to perform by hand, and are therefore rarely performed by human designers explicitly; to the best of the authors' knowledge, no CAD package incorporates such guidance. Derivation of the conditions also requires a bit of 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*.

This illustrates 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 a better procedures than those used by most designers, the expert system will in most cases match the expertise 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.

FAILURE OF DESIGN CHECKS - REDESIGN

Another problem that occurs in expert systems for design, is associated with what happens when a test fails. Checks against such things as 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-section 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.

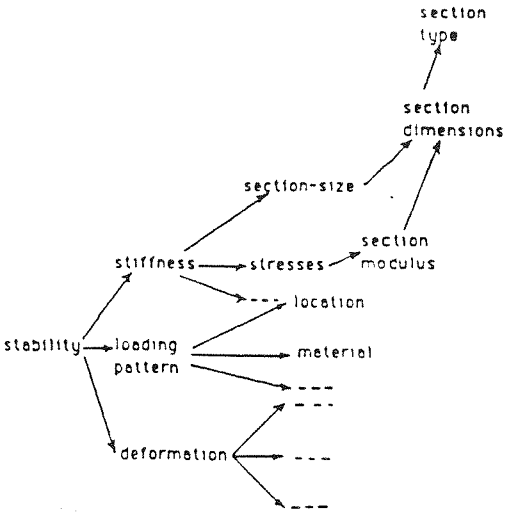

Figure 6. A portion of a dependency network (taken from Kumar and Topping [11]).

As an ultimate goal, but one which is probably not achievable in the forseeable future, the system should be able to work right at the limits of what is feasible. Thus, if a particular structure can only work by just satisfying all the available criteria, the system should eventually find such a design, although, like the human expert, it might have to work through many possible designs before settling on something that works. The system should not, however, do this by exhaustive search through all possible structures. It must do it by intelligent reasoning based on the rules that have been supplied by the author of the system, and the human experts consulted when it was written.

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 change that took place in analysis 20 years ago.

Structural analysis text books written pre 1960 concentrated on techniques for minimising 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-consuming 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.

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