Rationalization of Spine Beam Design for Expert Systems

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SUMMARY

The paper describes how the process of design of prestressed concrete spine beam bridges can be rationalised. This is done in the context of writing an expert system to carry out such designs, where the computer does the numerical calculations, and the engineer makes the decisions. It is shown that relatively few things have to be decided by the engineers, who can be helped by the computer calculatingbounds on the range of values from which the answer must be selected.

1. INTRODUCTION

Expert Systems appear to offer a great deal to design engineers; proponents of such systems imply that they will be able to completely automate the decision making process. Advances in computing power in the 1960s were matched by changes in the way analyses were carried out, primarily because existing analysis methods had been limited by the difficulty in solving simultaneous equations. But this revolution only affected *analysis* - it had little impact on the *design* process, except in as much as the analysis stage became faster. Indeed, it can even be argued that computer analysis made design worse. Engineers no longer had to think carefully about the structures they designed - the speed with which analysis could be carried out led to a procedure which can be described as *design by repeated analysis*. A trial structure was chosen and analysed; if it failed, modifications were made and the structure reanalysed, until it was satisfactory. By this process, the first design that satisfied the relevant criteria was chosen, with no thought given to whether it was the best.

Expert systems offer a way out of this problem, but, as will be shown later, preliminary work is needed. Knowledge-based expert systems incorporate information in the form of rules, which are typically in the form of

If A and B then do C and D

Provided the store of rules covers all aspects of the design of a particular type of structure, it is possible for the system to work through the rule base, drawing conclusions about the form the structure should take, and the various dimensions, before coming up with a final design. That, at least, is the theory. But where do these rules come from? All engineers know basic structural theory - some in more detail than others. Most engineers can describe why they took decisions in particular cases, but very few can generalise to produce generic rules needed to cover whole classes of structure.

The work described in this paper was carried out with a view to demonstrating that a different type of study is needed to make expert systems work properly for design (1). The design of prestressed concrete spine beam bridges was chosen for particular study, because of the background of the researchers (2) and because this is a field where competitive tendering for non-conforming designs is very common, indicating that many inefficient structures are still being designed.

2. NOVICE AND EXPERT DESIGNERS

We start with an analogy with human designers. A *novice* designer, when presented with a new problem, is unlikely to know where to start. Guesses are made, more or less at random, about the structural form, and many analyses are carried out. Improvements to the structure will result from questions of the form "What if I change this a little?", which is a procedure very similar to the strategies adopted in numerical optimisation.

As the designer becomes more experienced, less and less is done by way of guesswork. The underlying principles will be understood, so that decisions can be taken without major computation. The design will now evolve, with choices being made in a logical sequence. Simple calculations will be done, which allow major dimensions to be chosen. This then allows further calculations, after which more dimensions can be fixed. The design progresses in this way until it is complete. At some stage in the design process, a complete analysis needs to be carried out, if only to satisfy the checking authority, but the designer does this in the *expectation that the structure will be satisfactory*. Good design is not iterative, so effort is not wasted. Our designer has now become an expert, and we want our expert system to mimic this way of carrying out design.

In this paper, we show how the design of a prestressed concrete bridge falls naturally into three stages.

1. Determination of concrete cross-section,
2. Determination of prestressing force, and
3. Determination of cable profiles.

Many of the processes described will seem, obvious to the expert eye, but it appears never to have been written up in the literature; the authors of this paper were unable to find a clear statement of the way such bridges should be designed.

3. SECONDARY MOMENTS

We start by considering the way the designer wishes to deal with secondary moments (M_2). Some try to design structures without such moments, but they can be very beneficial, since they usually reduce the hogging moment over the piers (which are difficult to carry), while increasing the sagging moment at mid-span. There are two principal ways of dealing with secondary moments (3).

In *line of thrust design*, the engineer chooses a section to carry the bending moments due to the applied loads. An appropriate profile for the prestressing cable has to be found, which not only satisfies the stress limits on the structure, but is also concordant. This profile, which is the line of thrust of the cable (e_p), can then be moved by linear transformations to give the actual cable profile (e_s). e_p must satisfy inequalities of the form:-

$$e_p \geq -\frac{Z}{A} - \frac{Zf}{P} + \frac{M}{P} \qquad (1)$$

where M is the applied moment due to the load, P is the prestressing force, A is the cross sectional area, Z is the elastic section modulus and f is a stress limit.

The alternative method is *cable profile design*. The engineer chooses the magnitude of the secondary moments that will be present in the structure. These are added to the moments due to the applied load, and the cross-section is chosen. The designer then has to find a cable profile that not only satisfies the stress limits everywhere, but also generates the assumed secondary moments.

$$e_s \geq -\frac{Z}{A} - \frac{Zf}{P} + \frac{(M + M_2)}{P} \qquad (2)$$

The two methods are equivalent, and the choice between them is a matter of personal preference. In the line of thrust method, the designer needs no prior knowledge about the magnitude of the secondary moments that can be generated in a particular case, and there are methods available (4) which allow a concordant profile to be generated automatically. However, experienced designers normally use the cable profile method. They can estimate the amount of secondary moment that they are likely to be able to get, and they know how to modify cable profiles in order to be able to achieve it.

In the present design method, we will adopt the latter technique. We find that the amount of secondary moment present has an influence on the resulting structural dimensions, and for simplicity, we fix the amount of M_2 by defining the *reactant moment ratio* (RMR). The secondary moment must vary linearly along any bridge span, and must be zero at the ends. It is thus uniquely defined by the value of M_2 at the internal supports (which is taken to be sagging positive). This can be expressed as a fraction of the hogging bending moment due to the dead load of the structure (Figure 1.). The use of a non-dimensional ratio to specify the secondary moment means that the designer does not have to have prior knowledge of the actual value of M_2 and normalising it with respect to the dead load moment is more definitive than relating it to the live load moment. The value of RMR can vary from about 0.1 up to 0.5, and the choice of this value alters significantly the form of structure that results.

Figure 1. Calculation of Reactant Moment Ratio

4. CHOICE OF CROSS SECTION DIMENSIONS

We are now in a position to choose the cross-section dimensions. We assume:-

- We are dealing with road bridges, whose top flange is the road surface. This defines the width of the top flange.
- The top slab must carry local bending, which defines its thickness. (In the implementation of the expert system, we have a simple rule defining this thickness, but this could easily be replaced by a simple calculation).
- The thickness of the webs is controlled by practical detailing considerations, included in our implementation as a set of simple rules.

The engineer then makes a number of decisions, all of which can be expressed as simple ratios which can be based on experience.

- The overall depth of the structure is fixed, by specifying a span-to-depth ratio.
- The width of the bottom flange must be specified. In our implementation this is done by choosing the cantilever overhang on the deck and specifying the inclination of the webs.
- The engineer chooses the desired amount of secondary moment by specifying the RMR at each internal support.

Each of these decisions could have been implemented as rules, and we believe text books will, in future, give guidance on the choice of these factors, since they turn out to be the principal factors controlling the design. From this point onwards, nearly all the subsequent decisions can be based on logical deductions, which the computer program can make without additional guidance.

The only variable over which there is any significant freedom is the thickness of the bottom flange. This has to be chosen to satisfy three conditions.

1. The cross-section must have adequate resistance to hogging moment at the internal supports, which is governed by the compressive resistance provided by the bottom flange.
2. The range of stresses in the bottom flange, caused by the range of applied moments, must be less than the permissible stress range in the concrete. This is equivalent to saying that a valid Magnel diagram must exist at every cross-section. A feasible combination of prestress force (*P*) and eccentricity (*e*) must exist, which in turn means that the bound lines that pass through the Kern points must be separated by a positive amount (Figure 2.).

Figure 2. Magnel diagram

3. The section must be economic. This is controlled by considering the Magnel diagram again. We consider a section where the eccentricity is limited by cover requirements to e_{max}, which cuts across the feasible region of the Magnel diagram. If it cuts between points A and B, as shown in Figure 2, then a small change in e_{max} makes a relatively small change in the required prestressing force P. But if it cuts the feasible region between points B and C, the slope of the bound line is much steeper, requiring a much larger change in the prestressing force. We thus define point B as the *economic point* on the Magnel diagram, and we require that it lies within the range of permissible eccentricities.

These three conditions can all be expressed analytically in terms of the section dimensions, and the expressions rearranged to give limits on the area (or thickness) of the bottom flange. The designer is presented with the relevant value, and chooses the required bottom flange size.

Similar calculations can also be made on the size of the top flange, to check that the dimensions controlled by the practical assumptions made earlier are still valid, but this is done automatically and the designer only prompted for action if there is a problem.

5. CHOICE OF PRESTRESSING FORCE

The prestressing force throughout the beam then has to be chosen. This is again governed by a number of factors. These are based on the work of Low (5), which was rationalised by one of the authors (4), and extended by the other (1). There are essentially three factors that must be considered.

1. The prestressing force must lie within the limits set by the Magnel diagram. Thus:-

   $$P_1 < P < P_5$$

   P_1 corresponds to the minimum possible prestress needed to ensure that the tensile stress limits are just satisfied everywhere, while P_5 ensures that the compressive stresses are not exceeded. P_5 is not usually a governing condition, although its value can easily be calculated. These values vary along the length of the beam.

2. The prestressing force must be sufficiently high enough that a cable profile can be found to fit within the section. This corresponds to the force P_2 on the Magnel diagram, and in many cases is more critical than the value of P_1. This value also varies along the length of the beam.

3. A valid concordant profile must exist. This can be expressed as a condition on the prestressing force along the whole length of the beam. If a prestressing cable is placed at the lowest possible position in the beam it will produce greater sagging secondary moments than if placed at the highest possible position. The limits on the cable position can be expressed in terms of the line of thrust of the cable (e_p), and if a valid solution is to exist, a concordant line of thrust must exist between the limiting positions. The upper cable position must thus cause hogging secondary moments, and the lower position must cause sagging secondary moments. As pointed out by Burgoyne(4) this condition on the existence of a valid line of thrust can be expressed as lower limits on the magnitude of the prestressing force (P_3 and P_4). Jayasinghe (1) extended this work to cover cases where the prestressing force varies along the length of the beam.

Once the cross section has been chosen, the computer can calculate the magnitude of the prestressing force required at the middle of each span, and over each pier. The designer then chooses what force to apply, and where the cables are to be curtailed.

6. DETERMINATION OF CABLE PROFILE

The determination of the cable profile can also be automated significantly. To do this, we make use of the fact that the bending moment diagram corresponding to any notional loading on a structure must be a concordant profile. A method already exists for the automated determination of lines of thrust, which relies on iteratively seeking a notional load that generates a bending moment diagram that matches the desired line of thrust (4). It works by finding the biggest discrepancy between the current version of the line of thrust and the bounds on e_p. It then applies loads, chosen by considering the influence line for moment at the point in question, to correct the discrepancy. The process is repeated until a satisfactory profile is found. Although it involves iteration, which is something we are trying to avoid in an expert system, the process converges rapidly. The method has now been extended to deal with cases where the prestressing force varies along the length of the beam (i).

In the present implementation, we are working in terms of the actual cable profile, rather than the line of thrust. But since our desired e_s must have a concordant e_p, and since we have now chosen both P and M_2, we can rearrange the problem. Using P and M_2 we transform the limits on e_s to limits on e_p. We then find a suitable concordant profile, by the iterative method described above, which is transformed back to give us the required e_s. The result is a cable profile which both satisfies the stress limits, and also generates the required M_2.

7. IMPLEMENTATION OF EXPERT SYSTEM

The above principles have been implemented in an expert system BRIDEX. This uses the Edinburgh Prolog Blackboard Shell to hold the rules for the system (written in Prolog), and calls numerical and graphical display subroutines written in Fortran. It thus combines the optimum features of both computer languages. The programs run on an HP370 Unix workstation which has a good graphical display.

The program has been written using the principle that the computer should calculate whatever it can, and it should present to the designer any relevant limits on what the designer has to choose. The information should also be presented in a logical sequence, so that the design becomes more fixed as the process continues. The designer can then make those choices in the knowledge that iteration can be avoided, and in the certainty that subsequent analyses and checks will be successful.

During a typical run, the following procedures take place.

1. The designer has to specify the basic problem; spans, widths, loadings etc. These are normally part of the design brief and there is little scope for variation.

2. The designer chooses the amount of secondary moment, the overall depth of the bridge and the cantilever overhang.

3. The system analyses the structure to determine live load moment envelopes (6), and makes an estimate of the dead load. It then determines the limits on the bottom flange size, as described above, which it presents to the designer, who then chooses the actual dimensions.

4. The program determines the limits on the prestress at critical sections, which it presents to the user who chooses both the actual prestressing force to be applied, and the position at which the cables over the piers are to be curtailed.

5. The system calculates limits on the position and angle of the cable anchorages, whose actual values are then fixed by the user.

6. The program calculates a suitable cable profile (Figure 3) which satisfies the stress limits everywhere, and which generates the specified secondary moments.

Figure 3. Typical program output showing the automatically generated cable profile within the required bounds, for a 3-span beam. The cable force is limited by the existence of a feasible concordant profile, so the resulting profile is close to the upper bound over most of the beam length. The discontinuities occur at cable anchorage positions.

The system can print out current values of the principal variables, and can also produce plots showing the cross-section, cable profile, Magnel diagrams etc. as the design progresses.

8. FUTURE DEVELOPMENTS

Future improvements envisaged for the system include:-

- The use of non-prismatic sections, so that the cross-sections at mid-span and over the piers can differ.
- The inclusion of loads that arise due to the construction sequence, and the choice of prestressing cables at intermediate stages.
- The transverse analysis of the structure, with consequential effects on the cross-section, including splayed cross-sections.
- The determination of individual cable profiles, as well as the centroidal profile calculated here.

9. CONCLUSION

The process described here shows how careful thought about the sequence of operations allows a system to be written which deserves the title "expert". Decisions are taken about the way the design evolves in a logical order, with the computer doing what it is best at (i.e. calculating things), and the designers doing what they are best at (i.e. making decision based on their experience).

We believe that the BRIDEX system provides a model for the way such systems will evolve in the future. Not with masses of rules derived from discussions with engineers who refer to specific cases, but by careful consideration of the underlying principles. Once such knowledge has been obtained, we will see a corresponding change in the way text books are written, and in the way the subject is taught.

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