An Expert System For Prestressed Concrete Bridge Design

J.Sundaram[1] and C.J.Burgoyne[1]

Abstract

The development of an expert system, BRIDEX, for the design of prestressed concrete bridges is discussed in this paper. Design of multi-span continuous prestressed concrete bridges pose considerable difficulties to designers because of the large number of parameters involved and their complex interactions. The design is often perceived as an iterative process of generation, evaluation and modification of trial designs. It takes years of experience to develop an understanding of the design process. BRIDEX is aimed at providing guidance to the designers by suggesting appropriate range of values for the design parameters. The knowledge within BRIDEX is mainly based on fundamental principles developed by a careful study of the intricacies involved in the design process, while heuristics are used only to supplement this knowledge. The BRIDEX approach ensures that the whole design evolves sequentially as the design proceeds, module after module.

Introduction

The term 'expert system' refers to intelligent computer programs which contain knowledge-based component from an expert, such that the program can offer advice or take intelligent decisions on problems that require detailed experience in a particular domain. Engineering design is one such field where an expert system can be of immense help. The knowledge used during the design process is not well defined or articulated, so the goal is often reached iteratively. Past experience plays a dominant role in the design process, suggesting an expert system could guide less-experienced or novice designers.

In the present paper, the application of expert system techniques to the design of prestressed concrete bridges is explained. The *analysis* of prestressed concrete structures is well understood by many practising engineers and students, and is also well-documented. The difficulty arises in the *design* of prestressed structures; especially when applied to complex structures such as bridges which are built in stages. There are hardly any text-books or journal papers which cover the design aspect in detail, and it is absent from most university curricula.

---

[1] Engineering Department, University of Cambridge, U.K.

Current design knowledge

The initial design of a prestressed concrete beam mainly involves determining the cross-section dimensions, prestress force and the cable layout. The prime purpose of prestress is to enhance the behaviour of the beam at the serviceability limit state. So the initial design is, usually, produced to satisfy the limits on the concrete stresses; in particular, to resist the cracking of the concrete to an acceptable level.

For a simple statically determinate beam, the cable force and layout can be easily chosen once an appropriate cross-section has been selected. But for statically indeterminate structures, the selection of the prestress force and cable profile becomes very difficult due to the presence of the secondary moments (M_s). The prestress at any section then depends on the prestress force and layout at all the other sections. There are two principal ways of dealing with secondary moments (Burgoyne, 1988a); the line of thrust design and the cable profile design.

The *line of thrust design* method relies on generating a concordant profile, so that the secondary moments are zero. Thus, the secondary moments are not included directly in the design. This concordant profile corresponds to the line of thrust (e_p) of the cable, which has to satisfy a series of inequalities of the form:-

$$e_p \underset{\geq}{\leq} -\frac{Z}{A_c} - \frac{Zf}{P} + \frac{M}{P} \tag{1}$$

where M is the applied moment due to the load, P is the prestressing force, A_c is the cross-sectional, Z is the section modulus and f is the permissible stress in concrete. It needs to be ensured that the concordant line of thrust can also be linearly transformed to fit within the section boundaries.

In the *cable profile design* method, the magnitude of the secondary moments are estimated (or assumed) initially. These secondary moments are treated similar to the bending moment due to external loads. The designer has to find an actual cable profile (e_s) that satisfy series of inequalities of the form:-

$$e_s \underset{\geq}{\leq} -\frac{Z}{A_c} - \frac{Zf}{P} + \frac{(M + M_s)}{P} \tag{2}$$

In addition, the actual cable profile also has to generate the assumed secondary moments.

The two methods are equivalent, and the choice between them is a matter of personal preference. These methods differ in the way they treat secondary moments in the design process. Although secondary moments introduce additional degree of complexity in design, they can be beneficial in the redistribution of moments. Hence, experienced designers often use the cable profile design method as it gives them the freedom to choose the value of the secondary moments. It needs to be emphasised that the secondary moments cannot be calculated without knowing the cable force and layout, which inturn depend on the chosen value of the secondary moments. This process, thereby, tends to be very iterative.

In BRIDEX, the cable profile design method is used. The secondary moments are initially chosen in terms of their values over the intermediate supports; since these moments vary linearly between the supports their value at any position can then be determined.

The expert system BRIDEX

The expert system BRIDEX is built using the blackboard shell developed by Jones *et al.* (1986). The knowledge needed to solve the problem is partitioned into independent knowledge sources; these are separate and independent rules having a generalised *condition-action* format. These knowledge sources produce changes to the blackboard that lead incrementally to a solution. The communication and interaction between the knowledge sources take place solely through the blackboard. The changes to the blackboard are monitored by a scheduler (or control mechanism) which is built into the shell.

Each change to the blackboard constitutes an event that, in the presence of specific other information on the blackboard, can trigger (satisfy the condition of) one or more knowledge sources. Each such triggering produces a unique *knowledge source activation record* (KSAR). A KSAR is similar to an item on a task agenda. It represents a unique triggering of a particular knowledge source by a particular blackboard event. In each problem solving cycle, several KSARs may compete to execute their actions. The control mechanism determines which KSARs execute their actions and in what order.

Scheduler

The scheduler is the control mechanism which determines the execution of tasks. Subsequent to the addition of one or more entries to the blackboard, the rules that can utilise this new information are placed on an agenda which is constantly modified during the consultation process. The blackboard shell used in BRIDEX is a rule-based forward-chaining system, which means it works from what is already known to determine what can be derived. A typical *condition-action* rule in the blackboard shell has the following syntax:

`if`	*Condition*	(is the condition satisfied?)
`then`	*Goal*	(do something)
`to`	*Effect*	(what changes are to be made on the blackboard?)
`est`	*Est*	(helps resolve the conflict between the KSARs)

Knowledge base

The knowledge base of BRIDEX, at the moment, covers the main aspects of the design of prestressed concrete bridges; *viz* the selection of the cross-section dimensions and prestress. It is partitioned into the following knowledge modules:

1. Design briefs
2. Selection of the cross-section dimensions
3. Determination of the overall prestress force
4. Cable layout
5. Prestress for the intermediate transfer stages

The knowledge base is considered to be the heart of any expert system, and is the most important component which determines the success of the expert system. Hence, it is emphasised that, for design problems, the rules within the knowledge base should contain sound design principles, instead of heuristics, to the extent possible. Heuristics tend to be specific, and do not delve sufficiently into the design intricacies.

The aim of BRIDEX is to go through the design in a systematic way, thereby minimising redesign. The design has to satisfy the numerous inequalities, of the form shown in Equation (1) or (2), at the top and bottom fibres of every cross-section. These inequalities have to be satisfied for each loading condition; the *transfer* stage and *service* stage. For bridges built using segmental construction techniques, the design complexity increases due to the increase in the number of transfer stages. The design procedure is illustrated here for one such segmental construction technique; namely the *span-by-span* method.

In the present design approach, the governing conditions at the transfer and service stages are identified and taken into account early in the design process. The design parameters, in any particular knowledge module, are then selected based on the decisions taken in the previous modules and constraints to be satisfied in the subsequent modules. Each of these knowledge modules have a number of rules. The knowledge within these modules are briefly discussed below.

Module for design briefs

The design briefs consists of information which is obtained from the conceptual design stage. It includes the initial information such as the total length of the bridge, the number of supports, the number and width of the traffic lanes and footways, the form of construction, the construction sequence, the material strengths and the loading conditions. The information in this particular module is obtained typically through dialogues between the client, architect and designer, and is mainly a matter of achieving common goals. This information forms the initial input.

A typical rule in this module (in plain English) is of the form:

if the number of lanes is known
then ask the user for the width of each lane
and add the information on the blackboard, with full certainty.

Module for selection of cross-section dimensions

This module involves determining the section parameters, *viz* the shape of the cross-section, the longitudinal variation in the section geometry, and the sizes of the top flange, webs and bottom flange. The section dimensions are based on simple rules within the knowledge base. This module involves heuristics, logical rules and design algorithms. A simple representative application of a logical rule (again in plain English) is:-

if the webs are vertical
and the width of the top flange is known
and the top flange cantilever overhang is known
then calculate the width of the bottom flange equal to
the top flange width minus twice the overhang
and add on the blackboard the width of the bottom flange.

This design module also incorporates the calculation of the bending moments and the selection of the governing design criteria. At this stage, the designer also chooses the desired secondary moments. At the critical sections, the cross-section is then checked against a number of criteria discussed below:-

1. The minimum dimensions should be provided to ensure that the cables can be accommodated with sufficient cover.

2. The range of stresses within the section, 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 (Figure 1).

3. The section must be economic. Jayasinghe (1992) derived expressions for economical sections which can be illustrated by the Magnel diagram in Figure 1; this shows a section under dominantly sagging moments. For such a section, it is advantageous to have point B within the permissible section limit e_{max}, as it will ensure significant reduction in the minimum allowable prestress force (from P_5 to P_B) for only a marginal increase in the eccentricity or section depth (from e_A to e_B). Similar condition exist for a section under hogging moments.

The rules in this knowledge module ensure that proper section dimensions are selected and that a feasible force-eccentricity combination exist.

Module for determining the cable forces

Once the cross-section dimensions are fixed, the cable force throughout the beam needs to be chosen. The prestress force has to satisfy three conditions:

1. It must lie within the bounds set by the Magnel diagram; $P_1 < P < P_5$.

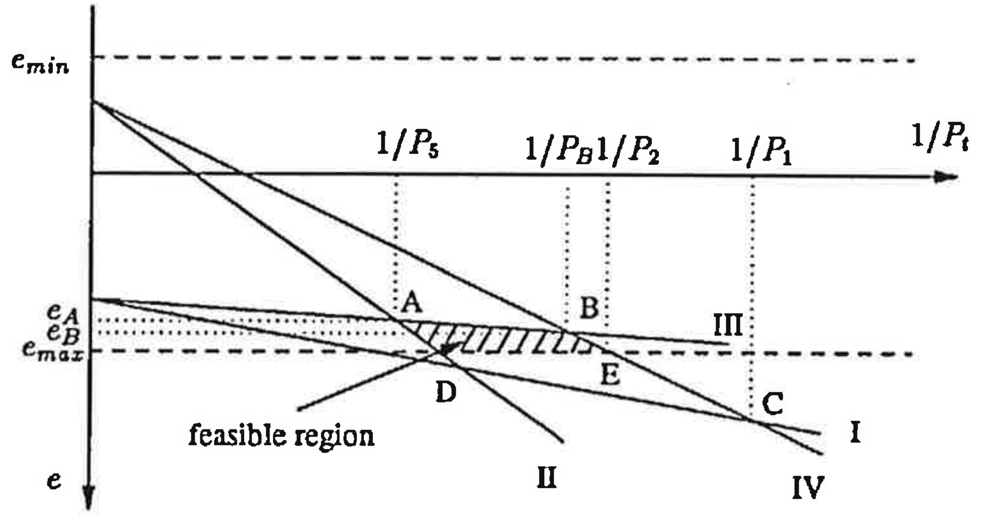

Figure 1: Feasible region on the Magnel diagram, for a dominantly sagging region, with $e_B \leq e_{max}$.

2. It must be large enough to ensure that a cable can fit within the section, as shown in Figure 1; $P > P_2$.
3. It must ensure the existence of a concordant profile within the bounds on the line of thrust, for the chosen prestress force. This condition will ensure that a cable profile can be determined later, as discussed in the next module.

This module consists of fundamental design principles written in a procedural language which are then loaded and linked with the rules in the knowledge base. The system calculates the limits on the prestress force and presents them to the user, who then chooses the desired values.

Module for determining the cable profile

The determination of the cable profile is also automated significantly using the concept of notional loads. It is well-known that the bending moment diagram corresponding to any notional loading on the structure must be a concordant profile. For the chosen cross-section dimensions and prestress force, the bounds on e_s are first determined, from Equation (2). Using the chosen values of the secondary moments (M_s) and the prestress force (P), the bounds on e_s are transformed to bounds on e_p using (from Equations 1 and 2)

$$e_p = e_s - \frac{M_s}{P} \qquad (3)$$

A concordant profile is then determined to fit the limits on e_p using an automated procedure (Burgoyne 1988b); this concordant profile is the line of thrust (e_p) for the cable. From Equation (3), the line of thrust can be transformed back to the actual cable profile (e_s). This cable profile will now satisfy the bounds on e_s and also generate the required secondary moment M_s.

A typical cable profile is shown in Figure 2.

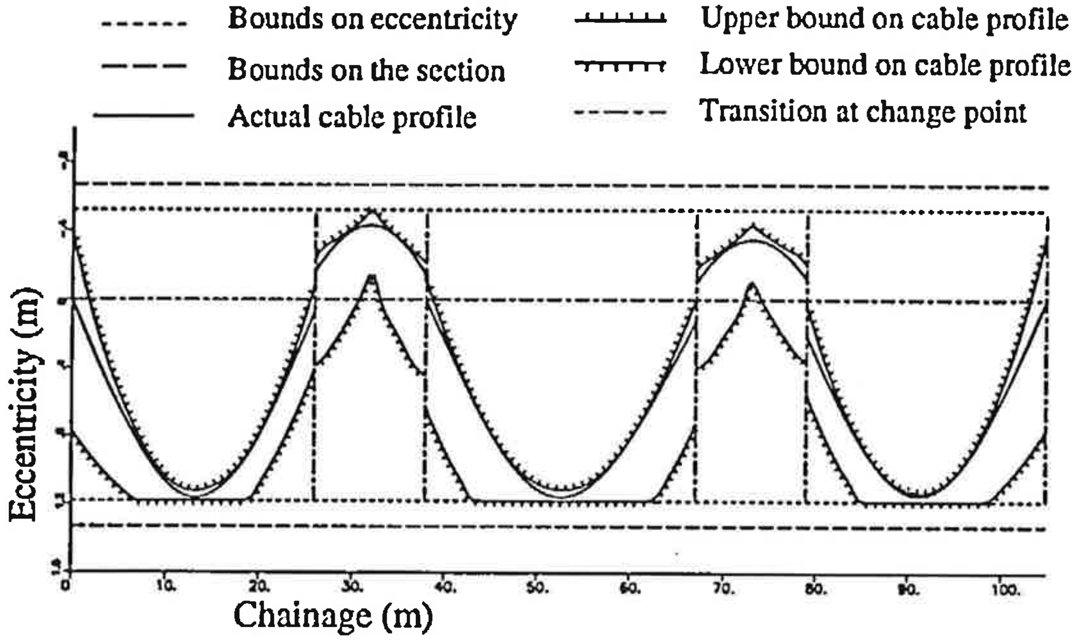

Figure 2: Actual cable profile.

Module for determining the prestress at intermediate transfer stages

The prestress force and cable layout for the intermediate stages are worked out in this module, working backwards from the final state, which is now known. At any stage, the prestress layout has to satisfy the corresponding stress limits in Equation (2), and at the same time must ensure that the cables sum to the final profile which is already known.

This module contains rules derived from fundamental principles, and the cable layouts are presented to the user in a graphical way. The prestress layout for a typical intermediate transfer stage is shown in Figure 3.

User interface

The expert system should be able to guide the user in taking proper decisions regarding the design parameters. BRIDEX has been written using the motto that the computer should perform all the menial calculations and all key decisions should be made by the designer, guided by the expert system. The system is, hence, so developed that the computer is made to do what it is best at (numeric processing, information storage and retrieval) while the designers do what they are best at (taking decisions and interpreting information).

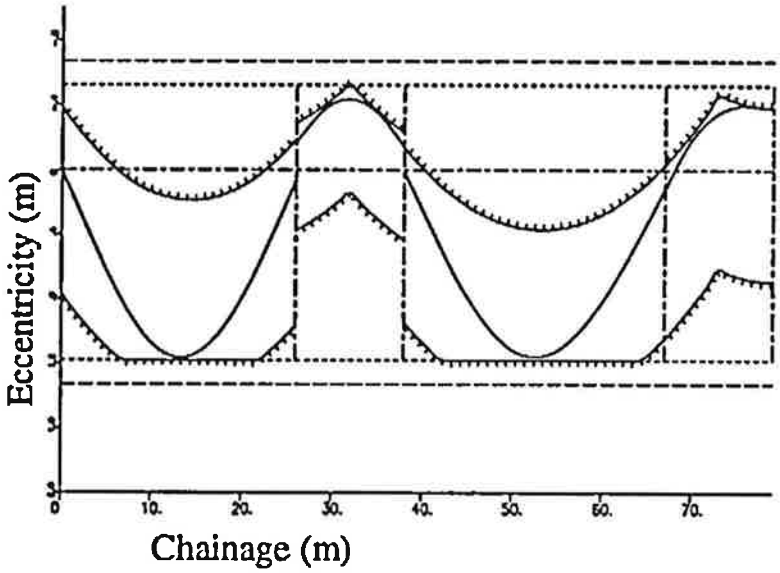

Figure 3: Cable layout at the end of second stage of construction.

Conclusion

The paper illustrates how good expert systems could be developed by carefully building up the knowledge base. By decomposing the design problem into separate knowledge modules, and by following a logical sequence of execution, the whole design solution evolves as the design proceeds. BRIDEX helps the designer to arrive at good design solution directly, rather than the iterative approach, and, at the same time it also helps the designers to develop an understanding of the design task and the interaction between the parameters.

Acknowledgement

Janardhan Sundaram gratefully acknowledges the financial support from the Cambridge Commonwealth Trust.

References

1. Jayasinghe, M.T.R. (1992). *Rationalisation of prestressed concrete spine beam design philosophy for expert systems.* Ph.D. Thesis, University of Cambridge.

2. Burgoyne, C.J. (1988a). Cable design for continuous prestressed concrete bridges. *Proc. Instn. Civil Engineers*, Part 2, Vol. 85, pp 161-184.

3. Burgoyne, C.J. (1988b). Automated determination of concordant profiles. *Proc. Instn. Civil Engineers*, Part 2, Vol. 85, pp 333-352.