A NOVEL APPROACH TO PRESTRESSED CONCRETE BRIDGE DESIGN

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Design of prestressed concrete bridges is normally performed through an iterative process of generation, evaluation and modification of trial designs. The presence of secondary moments in continuous structures and the effects of concrete creep in segmental construction, complicate the design task. Inexperienced designers often find themselves carrying out an endless repetitive search for a feasible solution. The paper describes a technique which helps carry out design, not by repeated alterations to the chosen trial section and cable geometries, but by evolving the solution as the design proceeds. The design is carried out in modules with decisions on the parameters taken sequentially. The method has been implemented in an expert system, although it is equally applicable to more conventional design approaches.

INTRODUCTION

The design of engineering structures follows three broad stages: conceptual design, preliminary design and detailed design. There is no well-defined demarcation between these stages. Although they perform different roles and fulfil varying criteria, they are related. Conceptual design is the early stage where the structural layout and the form of construction are decided. It involves dialogue between the client, architect and designer. In the preliminary design stage, the overall structural form is selected satisfying a few key design constraints. Past experience plays an important role in the choice of the preliminary section. The detailed design involves analysis of the chosen structure from the preliminary stage, and modifications to the trial design so as to satisfy all applicable constraints. This stage follows an *analysis-sizing-checking-redesign* cycle. The amount of time spent at the detailed design stage and the number of redesign cycles undertaken are proportional to the complexity of the problem, the understanding of the principles and the experience of the designer. Novice designers spend a lot of time at the detailed design stage, and are forced to carry out a tiresome iterative search for the solution. This arises due to poor choice of the preliminary solution. On the other hand, experienced designers, based on their previous knowledge and judgement, are able to suggest preliminary solutions needing very little modification at later stages. Good designs are rarely arrived iteratively. The paper presents an approach to prestressed concrete bridge design, to guide engineers to arrive at good design solutions, without the necessity for redesign. The major design constraints were identified and suitably incorporated in the design approach, so that subsequent design decisions taken would satisfy all these constraints.

Why deal with prestressed concrete bridge design principles? Bridge design is one of the most complex tasks posed to designers because of the large number of design parameters involved, and their complex interactions. The analysis of prestressed concrete structures is well understood. However, there are hardly any text-books or research papers which cover the design aspects, especially for complex structures like bridges. The lack of design knowledge makes the iterative process tedious, and calls for a better understanding of the design principles.

DESIGN CRITERIA

Prestressed concrete structures are normally designed to fulfil stress criteria under serviceability conditions, and later checked for strength under ultimate limit state conditions. For a statically determinate beam, if M is the external moment acting at a section, P the prestressing force acting at an eccentricity e_s, and f_c and f_t are the permissible stresses in compression and tension, then there will be a series of stress conditions of the general form:-

$$f_c \le -\frac{P}{A} - \frac{P.e_s}{Z} + \frac{M}{Z} \le f_t \qquad (1)$$

where Z corresponds to the section modulus of the extreme fibres.

In statically indeterminate structures, secondary moments (M_2) produced by the prestressing forces also need to be considered, in addition to the primary moments ($-P.e_s$). Equation (1) thus becomes,

$$f_c \le -\frac{P}{A} - \frac{P.e_s}{Z} + \frac{M + M_2}{Z} \le f_t \qquad (2)$$

The secondary moments make the cable appear to act at a different position, the line of thrust (e_p), given by:-

$$P\, e_p = P\, e_s - M_2 \qquad (3)$$

The presence of secondary moments makes the design complex, as they are a function of the prestress layout which initially is not known. However, they can be very beneficial in redistributing the hogging moment over the piers to the sagging moment at mid-span.

As bridges are built in stages, the chosen design should satisfy the stress criteria (Equation (2)) at each transfer stage and at the service stage, taking into account the prestress losses and creep effects.

DESIGN APPROACH

The support positions and construction sequence are assumed to be known before-hand. The width of top flange is fixed based on the number of lanes, width of lanes, and width of foot paths and hard shoulders specified by the client. The live load moment and super-imposed dead load moment are worked out based on the design loads to be carried on the bridge. Having defined the grade and permissible stresses in concrete, the design follows the sequence given below:-

1. Choice of cross-section dimensions
2. Determination of prestressing force
3. Cable layout
4. Determination of prestress force and cable layout at intermediate stages

The aim of the present work is to go through the above procedure once to avoid iterative search. To do this, the governing criteria are identified and taken into account from the very start of the design process. Initially, the conditions existing at the completion of construction (*Initial transfer*) and at the service stages are taken into consideration, and all key design parameters (Items 1 to 3) are worked out. The stress criteria for the intermediate transfer stages are later satisfied by proper distribution of the prestress, as explained under Item 4.

Before covering the determination of the design parameters in detail, the major factors due to segmental construction which are taken into account are explained. The design principles are explained here for prestressed concrete bridges built using the *span-by-span* method of construction only. However, similar effects also occur in other construction techniques such as balanced cantilever, progressive placement and incremental launching.

FACTORS AFFECTING DESIGN

Effect of construction sequence on dead load moments

Figure 1a shows a typical construction sequence. The superstructure is built in one direction, by means of a form traveller. Any stresses existing in the structure, at a particular stage, are considered 'locked in' and carried forward to the next stage. The dead load moments at each stage thus depends on the actual sequence of construction.

At any jth transfer stage, the total dead load moment is

$$M_{dl} = \sum_{i=1}^{j} (M_{dl})^i \qquad (4)$$

where $(M_{dl})^i$ represents the dead load moment at a particular i^{th} stage of construction. For simplicity of presentation here, creep effects during construction are ignored, although they are taken into account in the full analysis.

Effect of stage prestressing

As the segments are built, they are prestressed in stages. In order to maintain continuity with the preceding segments, the cables overlap in the support regions as shown in Figure 1b. The secondary moments caused by the prestressing cables, are additive, as for the dead load moments discussed above.

At any jth transfer stage, the total secondary moment is,

$$M_{2t} = \sum_{i=1}^{j} (M_{2t})^i \qquad (5)$$

where $(M_{2t})^i$ represents the dead load moment at a particular i^{th} stage of construction. The prestress losses which occur between the individual construction stages have not been accounted in the above formulation.

Effects due to concrete creep

Creep of concrete tends to create a time-dependent variation of the bending moment within the structure, from the initial built-up condition to that which would have existed had the structure been built in its fully continuous state (England (1)). In segmental construction, where the initial built-up moments vary considerably from the monolitic moments, creep effects are important and need to be determined or a reasonable estimate drawn at the preliminary stage.

CHOICE OF DESIGN PARAMETERS

Cross-section dimensions

Most of the section dimensions can be chosen by simple criteria. The top flange width has been already fixed by the client. The number and spacing of the webs are decided based on the width of the top flange. The top flange has to resist local bending which governs its thickness, defined by simple guide-lines. The thicknesses of the webs are based on practical detailing considerations, depending on the presence or absence of prestressing cables within them. The overall depth of the structure is specified by the *span-to-depth* ratio. The width of the bottom flange is based on the cantilever overhang and web inclination chosen from local bending and aesthetic considerations.

The only other parameter yet to be chosen is the thickness of the bottom flange. The minimum thickness of the bottom flange is initially chosen based on detailing considerations ensuring that the cables can accommodated with sufficient cover. From the chosen cross-section dimensions, the dead load moments are evaluated. Creep effects are calculated knowing the actual construction sequence. Secondary moments are key variables for design, and their values over the internal supports are initially estimated. As the live load moments are already known, the range of moments to be designed for is thus determined. From the series of stress criteria existing under initial transfer stage and service stage, only four governing criteria need to be considered at any section, from which all subsequent design decisions evolve.

The chosen cross-section is checked against the following criteria, suggested by Burgoyne and Jayasinghe (2):-

- The bottom flange must ensure adequate resistance to hogging moment over the internal supports, which is governed by the compressive resistance provided by the bottom flange.

- In order to ensure a valid solution, the selected cross-section is checked for the existence of a feasible Magnel diagram, within the boundaries of the section. This means that the bound lines that pass through the Kern points must be separated by a positive amount (Figures 2 and 3). Hence,

  Slope of line III ≤ Slope of line I

  Slope of line IV ≤ Slope of line II

- In addition, to ensure an economic section, the following additional conditions are imposed which ensure a large saving on prestress for a relatively small change in the eccentricity limits:-

  $e_B \leq e_{max}$ .... for dominantly sagging regions

  $e_D \geq e_{min}$ .... for dominantly hogging regions

The above three criteria can be rearranged to give limits on the thickness of the bottom flange. If needed, the cross-section is modified at this stage.

Determination of Prestressing force

After choosing the cross-section dimensions, the prestressing force is selected based on the following conditions:

- Bounds on the Magnel diagram - The prestressing force must satisfy,

  $$P_1 < P < P_5$$

  where the values for P_1 and P_5 are as shown in Figures 2 and 3.

- Bounds set by section depth - In order to ensure that the cable fits within the section, with due regard to the cover requirements, the force P must satisfy,

  $$P > P_2$$

- Existence of a valid concordant profile - The cable profile should have a corresponding concordant profile which lies within the bounds on the line of thrust. The design rationale is based on the work done by Low (3) and Burgoyne (4). A cable placed at a higher position in a beam will produce lower sagging secondary moments, while a cable placed at the lowest possible position will produce higher sagging secondary moments. For a valid concordant profile to exist, the upper bound on the line of thrust must cause hogging secondary moments and the lower bound must cause sagging secondary moments. In addition, the cable profile has to be smooth between anchorage positions, while the bounds on the line of thrust itself usually have sharp peaks over the supports. These conditions can be expressed as lower bounds on the prestressing force.

Having decided on the anchorage positions, the prestress variation along the bridge beam is chosen from the above criteria.

Determination of cable profile

For the chosen cross-section dimensions and prestressing forces, a cable profile has to be found which satisfies the bounds on the Magnel diagrams everywhere and also produces the secondary moments assumed earlier. The bending moment diagram corresponding to any notional loading on the structure is a scaled concordant profile, as they produce deformations compatible with zero displacements at the supports. To use this concept to advantage, the bounds on cable profile (e_s) are transformed to bounds on line of thrust (e_p), using Equation (3). A concordant profile is then determined satisfying the bounds on e_p, using the concept of notional loading as proposed by Burgoyne (5). The corresponding cable profile e_s is found by back-transforming the concordant profile e_p (Figure 4).

Prestress at intermediate transfer stages

After having chosen the overall prestressing force and layout, the prestress distribution at each intermediate transfer stage is determined, so as to satisfy the stress criteria for that stage. The secondary moments generated at the completion of the construction sequence have to lie within estimated limits. As explained earlier, the total secondary moment at any transfer stage is the sum of the secondary moments over all the preceding stages. The prestress layout at intermediate construction stages are therefore worked out in the reverse order, starting from the last stage. At any particular stage of construction, the prestress distribution is chosen to ensure that the secondary moment over the corresponding penultimate support lie within permissible range. The layout of the cable is chosen to satisfy the limits on the Magnel diagram at that stage, as shown in Figure 5, and at the same time ensuring that the cables sum to the final layout. The profile can be either chosen by the designer or else is worked out automatically based on the position and inclination of the jacks.

DISCUSSION

From the above procedures, it can be seen how the parameters follow smoothly during the design process. Once the parameters have been chosen, a final check can be carried out, if needed. The design approach has been incorporated in an expert system for bridge design. The program has been so developed that the decisions on the parameters are taken by the designer, guided by limits based on above principles. Thus the flexibility of the designer is not hampered.

CONCLUSIONS

The paper illustrates that good design methods could be developed by a careful study of the design process and the associated intricacies. By taking account of governing parameters and the factors affecting design early in the design process, the approach adopted ensures that the whole design evolves in a logical sequence, without the need for redesign. Most of the above principles, although described here for bridge design, could be extended to other prestressed concrete structures.

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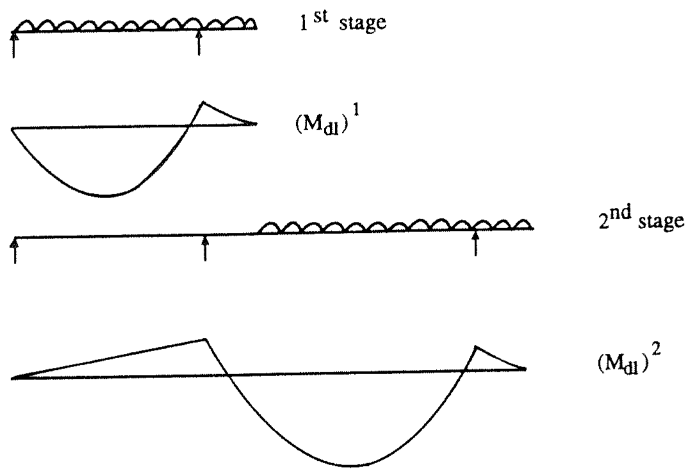

Figure 1a Actual dead load moment diagram

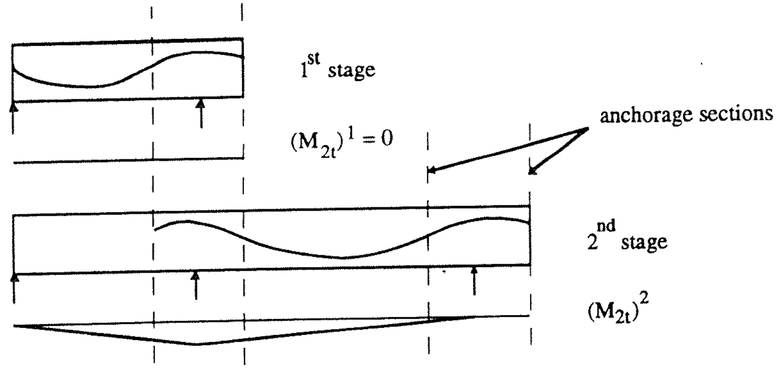

Figure 1b Secondary moment diagram due to stage-prestressing

Figure 1 Moments due to span-by-span construction

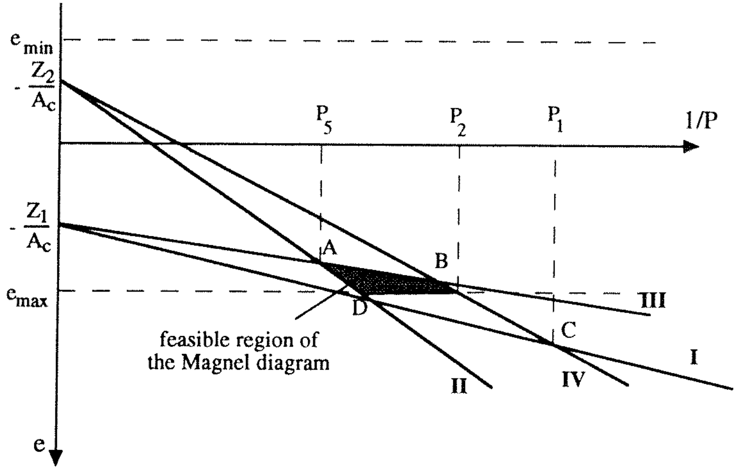

Figure 2 Magnel diagram for dominantly sagging region

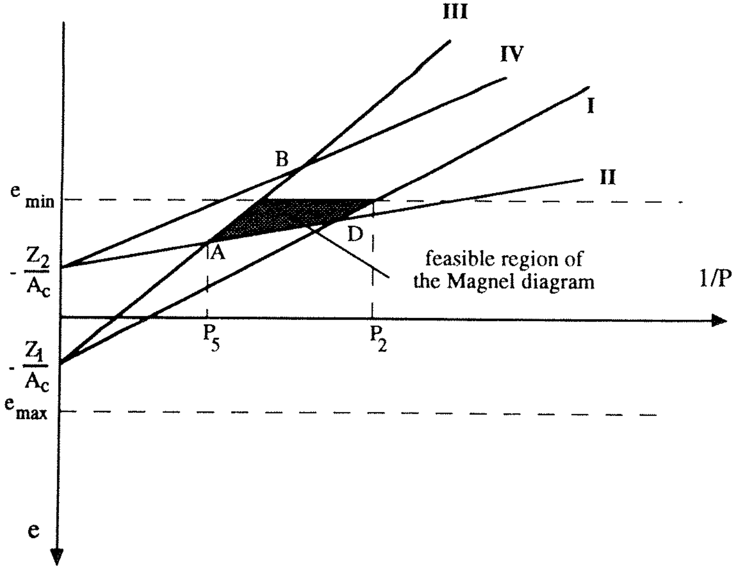

Figure 3 Magnel diagram for dominantly hogging region

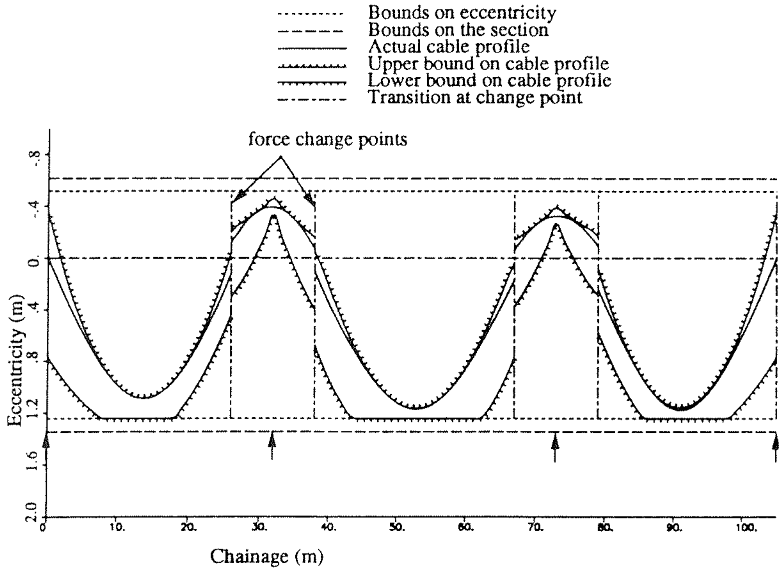

Figure 4 Cable profile

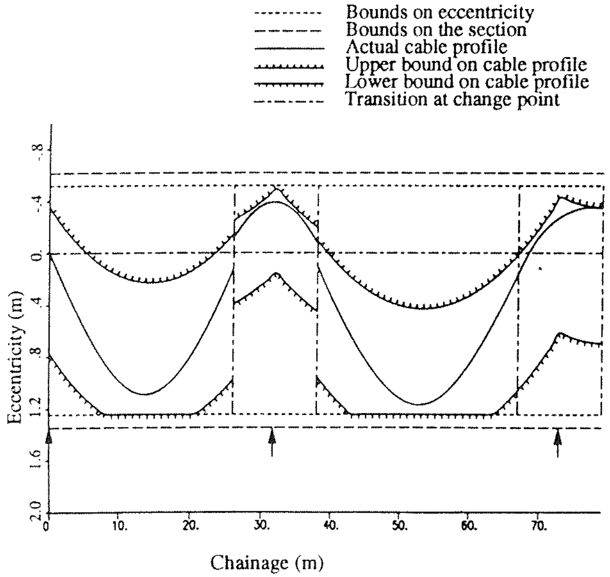

Figure 5 Cable profile at the end of stage 2, satisying the corresponding eccentricity bounds