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DEVELOPMENT OF AN EXPERT SYSTEM FOR THE DESIGN OF PRESTRESSED CONCRETE BRIDGES

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Abstract

The paper describes the development of BRIDEX, the BRIdge Design EXpert system, for design of prestressed concrete bridges. Design of multi-span continuous prestressed concrete bridges poses considerable difficulties because of the large number of design parameters, the number of design constraints imposed by the medium and codes of practice, and complex interactions between these parameters and constraints. The design is usually carried out as an iterative process of generation, evaluation and modification of trial designs. The dearth of design principles necessitates years of experience from designers before they are able to successfully carry out bridge designs. BRIDEX is aimed at developing an understanding of the design process and guiding the designer by suggesting appropriate ranges of values for the design parameters.

1 Introduction

An expert system is an intelligent interactive computer program which should emulate an expert and provide advice on problems that require vast experience in a particular domain. Expert Systems can be of immense help to bridge engineers. Bridge engineering is the most competitive field in the construction industry which is evident from the number of bids submitted for any project proposal. However, there are wide margins between the tender estimates. Competitive tendering for non-conforming designs is very common indicating that many inefficient structures are still being designed.

Analysis of prestressed concrete structures is well understood by many practising engineers and students; it is the process of evaluating the performance/ suitability of a known structure under the action of given loads and constraints. With the advent of computers, there have been rapid developments in various analytical techniques. But where do we stand in terms of design? How many colleges and universities, text-books and research papers cover the design aspect in detail? The lack of design knowledge forces *novice* engineers to adopt a tiresome iterative process of design by repeated analysis. A trial structure is chosen and analysed; if it fails, modifications are made and the structure re-analysed until it is satisfactory. It is the lack of good design principles which motivated the authors to undertake the work described in this paper.

2 Design Expert Systems

Engineering design involves three broad stages: conceptual design, preliminary design and detailed design. Although the three stages perform different roles and fulfil varying criteria, they are related to each other.

Conceptual design is the early stage of the design process which deals with the conception of the structural layout and the form of construction. This stage involves dialogue between the client, architect and designer. A small amount of experience does come into play, but this is mainly a matter of achieving common goals.

Preliminary design involves the selection of overall structural form of the *artefact*, satisfying a few key design constraints. Human experience plays a significant role at this stage. Decisions taken here are based on the criteria to be satisfied at the detailed design stage. Similarly, the decisions at the detailed design stage are governed by the parameters chosen at the preliminary design stage. A good expert system should thus integrate the preliminary and the detailed design. When presented with a new problem, novice designers are often perplexed and unlikely to know from where to start. Guesses are made more or less at random about the structural form. The later design modifications at the detailed design stage and the amount of redesign depend on the preliminary design. A novice designer has to spend a lot of time on redesign. As the designer becomes more experienced, fewer decisions are taken by guesswork. Good design should involve the least amount of iteration. The designer should consider all key governing factors while selecting design parameters at the preliminary design stage, so that subsequent checks at the detailed design stage will be successful.

Detailed design involves detailed analysis of the chosen structure from the preliminary design, and sizing or proportioning of its components so as to satisfy all applicable constraints. Thus the process involves three main sub-tasks:

a) Analysis of the chosen structure
b) Sizing and proportioning of the components
c) Checking all applicable design constraints

In order to satisfy all applicable constraints, this stage typically follows an *analysis-sizing-checking-redesign* cycle. Feedback for redesign is based on judgement and experience of the designer.

Many of the existing Expert Systems for design are based purely on heuristic rules or on database search. They rely heavily on redesign due to the deficiency of the preliminary solutions. It can easily be argued that heuristics alone are not capable of taking into account the many intricacies in design. The database approach seems to cover only specific cases and hence there is lot of uncertainty involved. Design should be based on fundamental principles as far as possible in addition to simple heuristic rules which are based on past experience. The expert system should thus integrate algorithms written in procedural languages covering the design principles with heuristics written in a declarative language.

3 Development of BRIDEX

BRIDEX is an expert system being developed at the University of Cambridge for the design of prestressed concrete bridges. A schematic representation of the architecture of BRIDEX is shown in Figure 1.

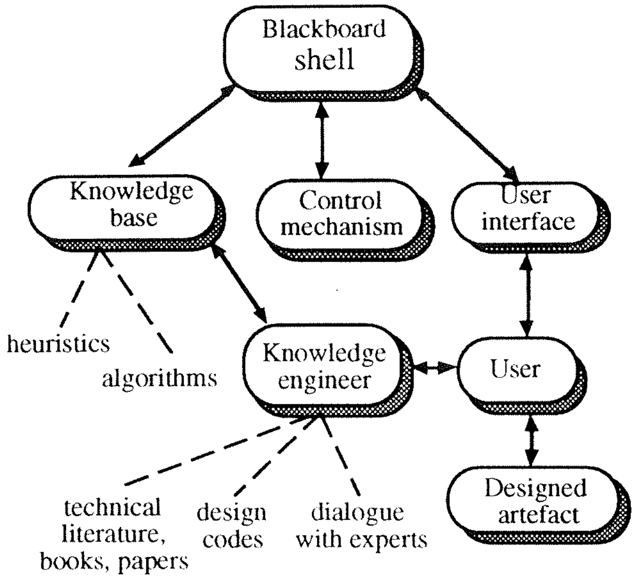

Figure 1. Architecture of BRIDEX

BRIDEX is being developed using the Edinburgh Prolog Blackboard Shell (EPBS). The main components of BRIDEX are explained below.

3.1 Knowledge Base

The knowledge base of BRIDEX has two main knowledge modules pertaining to the preliminary design (Figure 2a) and detailed design (Figure 2b). Each of these modules have a number of sub-modules.

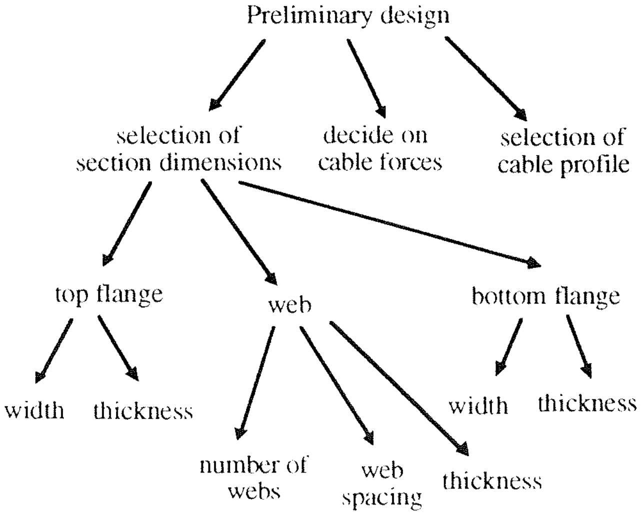

Figure 2a. Module for preliminary design

The knowledge base consists of heuristic rules and design algorithms interfaced together. The heuristic rules are written in Prolog while the design algorithms are written in Fortran and C.

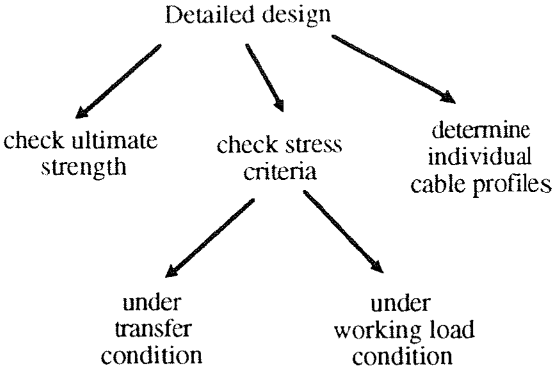

Figure 2b. Module for detailed design

3.2 Control mechanism

The control mechanism or the scheduler determines the sequence of execution of tasks based on *est*, an estimate of the usefulness of rules in the knowledge base. Rules are assigned a value of *est* which ensures that the rules are triggered, in the first instance, in the most logical sequence. Exhaustive searches involving non-optimal sequences are still possible.

3.3 User interface

A graphical interface is provided which enables selected cross-section, bending moment envelopes, permissible limits on cable forces and cable layout to be presented graphically to the designer.

4. Design Principles

At present, BRIDEX can design prestressed concrete bridges built by the *span by span* method of construction, which is often adopted in the case of long viaducts with relatively short spans. In this form of construction, the superstructure is built in one direction, by means of a form traveller. As the segments are assembled in stages, progressive prestressing is carried out to provide structural integrity and also to resist the dead load moments. The prestressing cables overlap in the support region with the anchorages on either side of the intermediate supports.

Before covering the design criteria, it is necessary to understand secondary moments and the ways of dealing with them.

4.1 Secondary moments (M_2)

When a continuous prestressed concrete beam is prestressed, a set of self equilibrating reactions are produced at the supports to maintain compatibility. These reactions generate moments called secondary (or reactant) moments in addition to the primary moments due to prestress. If at a particular section, M is the external bending moment acting and P is the prestressing force in a cable placed at an eccentricity e_s, then the effect of the secondary moment (M_2) is to make the cable appear to act at a different position e_p called the line of thrust, where

$$P\, e_p = P\, e_s - M_2$$

A profile placed at the line of thrust will induce zero secondary moment and is termed a concordant profile.

There are two ways of dealing with the secondary moments; the line of thrust design method and the cable profile design method. The two methods are equivalent and the choice between them is a matter of personal preference.

In the *line of thrust* design method, secondary moments are treated as prestressing effects. There will be a series of stress conditions of the general form

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

where Z is elastic section modulus, A is the cross sectional area and f_c and f_t are permissible compressive and tensile stresses respectively.

The designer has to find a concordant profile which satisfies these limits. It must also be possible to linearly transform the concordant profile to fit within the section boundaries.

In the *cable profile design* method, secondary moments are treated as loads and they appear in the eccentricity equation with the applied loads. The limits on the actual cable profile e_s can then be written as,

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

The designer initially estimates the secondary moments that will be present in the structure and then has to find a profile which not only satisfies these limits but also generates the assumed value of M_2.

Secondary moments can be very beneficial in the redistribution of moments. In line of thrust design, the designer has no idea of the magnitude of secondary moments that will be generated. Experienced designers normally use the cable profile design method, as they are able to estimate the amount of secondary moments that they are likely to get and can take full benefit of M_2. BRIDEX adopts the cable profile design method.

4.2 Design Criteria

At any particular section, inequalities of the form shown in equations(1 or 2) have to be satisfied for both the top and the bottom fibres at the service stage as well as at each transfer stage. The transfer stage is the condition existing during construction when only dead loads are acting on the structure, and the full prestress is considered in design without any losses. At service or working stages, all loads are considered in the worst combination, and the prestress losses are taken into account. The design takes into account the conditions existing at both the initial transfer stage and the final service stage, before deciding on the values for the design parameters. The design of prestressed concrete bridges then evolves logically, with the decisions on the key design parameters taken sequentially as the design proceeds. The design process and the choice of the design parameters are explained below.

4.2.1 Determination of concrete cross-section dimensions

The various criteria governing the cross-section dimensions are given below:

- The width of the top flange is fixed, based on the width of lanes, number of lanes, width of parapet wall and width of foot/ cycle paths.
- Top flange thickness is governed by its local bending capacity. This is based on simple heuristic rules.
- The thickness of the web is based on practical detailing considerations, included as a set of simple rules within BRIDEX.
- The overall depth of the structure is fixed by specifying the *span-to-depth* ratio as suggested by the system.
- The width of the bottom flange is defined by choosing the cantilever overhang of the deck and by specifying the inclination of the webs.

From this stage onwards, nearly all the subsequent decisions can be based on logical deductions, which the program can make without additional guidance.

The thickness of the bottom flange can now be determined. This should satisfy the following conditions:

1. The cross-section must have adequate resistance to hogging moment, which is governed by compressive resistance provided by the bottom flange.
2. The minimum thickness is based on detailing consideration which ensures that the cables can be accommodated within the bottom flange, with due regard to the cover requirements.
3. It should ensure the existence of a feasible region on the Magnel diagram, which is a plot of eccentricity (e) versus the inverse of prestressing force (P). A feasible Magnel diagram ensures that the bound lines passing through the Kern points are separated by a positive amount (Figure 3 and Figure 4).
4. The section must be economic. The conditions for an economic section can be shown from the Magnel diagrams (Figure 3 and Figure 4) to be,

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

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

The above conditions show that for a small change in the eccentricity limits, there can be a relatively large saving on the amount of prestress.

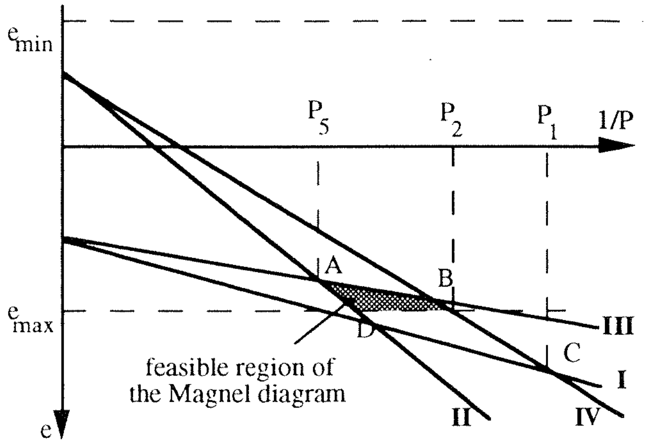

Figure 3. Magnel diagram for sagging region

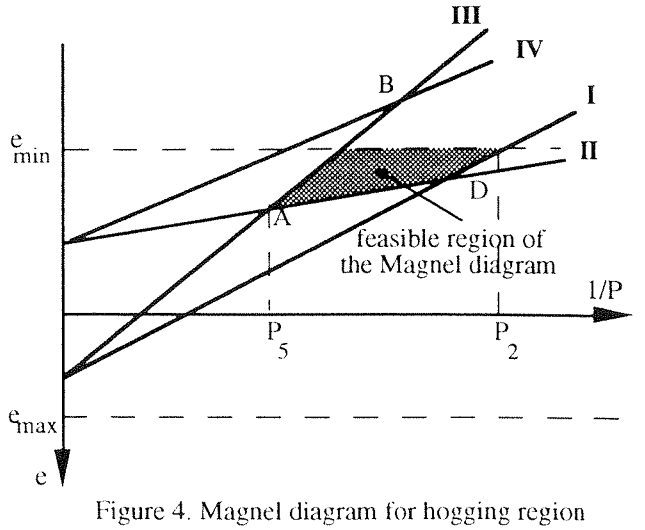

Figure 4. Magnel diagram for hogging region

4.2.2 Determination of prestressing force

Once the cross-section dimensions have been fixed, the prestressing force has to be now chosen. The design rationale is based on work done by Burgoyne[1] and Jayasinghe[3]. There are a number of factors.

- The prestressing force must lie within the bounds set by the Magnel diagrams (Figures 3 and 4).

  $$P_1 < P < P_5$$

  P_1 and P_5 ensure that the permissible tensile stresses and compressive stresses are not exceeded. These values vary along the beam.
- The prestressing force must be high enough to ensure that a cable can fit within the section, as shown in Figure 3 and Figure 4.

  $$P > P_2$$
- It must ensure the existence of a valid concordant profile. A cable placed at the lowest possible position in the beam will produce greater sagging secondary moments than if placed at the highest possible position. A similar argument applies to the cable placed at the lower and upper limits on the line of thrust. For a valid concordant profile to exist, the upper limit on the line of thrust must cause hogging secondary moment and the lower limit must cause sagging secondary moment. This condition can be expressed as lower limits on the prestressing force (P_3 and P_4).

Based on the above conditions, the program calculates the magnitude of the prestressing force in the span and support regions from the design moments existing under the transfer and service stages.

4.2.3 Determination of cable profile

The determination of the cable profile has also been automated significantly using the concept of notional loads. It is known that the bending moment diagram corresponding to any notional loading on the structure must be a concordant profile. A method already exists for the automated determination of the line of thrust (e_p), which relies on seeking a notional load that generates a bending moment diagram satisfying the limits on e_p [2]. The bending moment envelopes, for most structures, will show peaks in hogging bending over the internal supports. The actual cable profile e_s has to be smooth over the piers, although the line of thrust may itself have a kink at that position.

Having chosen the cross-section dimensions, prestressing force and the amount of secondary moments, the limits on e_s are determined. Using the prestressing force and secondary moments, the limits on e_s are transformed to limits on e_p. A concordant profile is then determined to fit the limits on e_p using the notional load method. A predetermined kink is introduced in the concordant profile over internal supports so that the resulting cable profile e_s will be smooth (Figure 5).

The corresponding cable profile e_s will now satisfy the stress criteria under the service stage and the transfer stage, and also generate the required M_2.

4.2.4 Prestress at each intermediate transfer stage

The prestressing force and cable layout at each intermediate transfer stage have to be now determined so as to satisfy the stress criteria at that stage. The secondary moments generated at the end of the whole construction sequence, have to satisfy the values of M_2 assumed initially. The prestressing force and cable layout are therefore worked out in reverse order, starting from final construction stage. At any i^{th} stage, the cable force over the i^{th} support is chosen to satisfy the limits on M_2 over that support, based on all succeeding construction stages. The prestressing force in the span region can also be applied either in full or in part as construction proceeds. The layout of the cable at any stage is chosen so as to satisfy the limits on the Magnel diagram at that stage, as in Figure 6, and at the same time to ensure that the cables sum to the final profile worked out earlier in section 4.2.3.

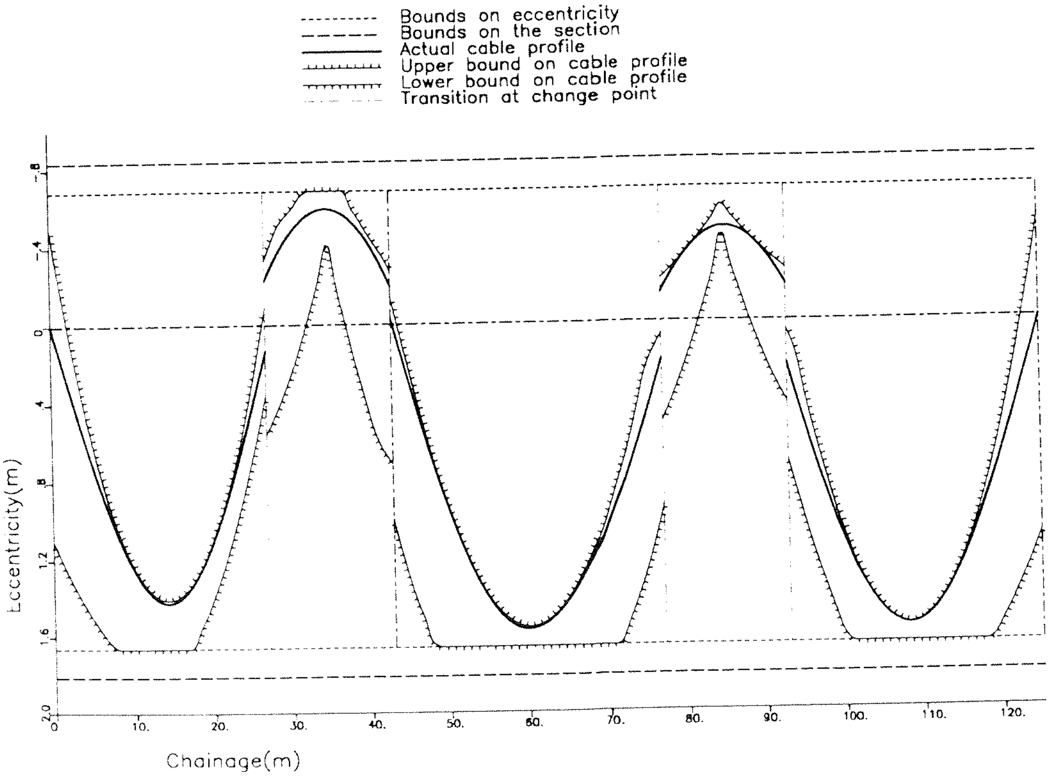

Figure 5. Typical plot of actual cable profile satisfying the cable profile zone

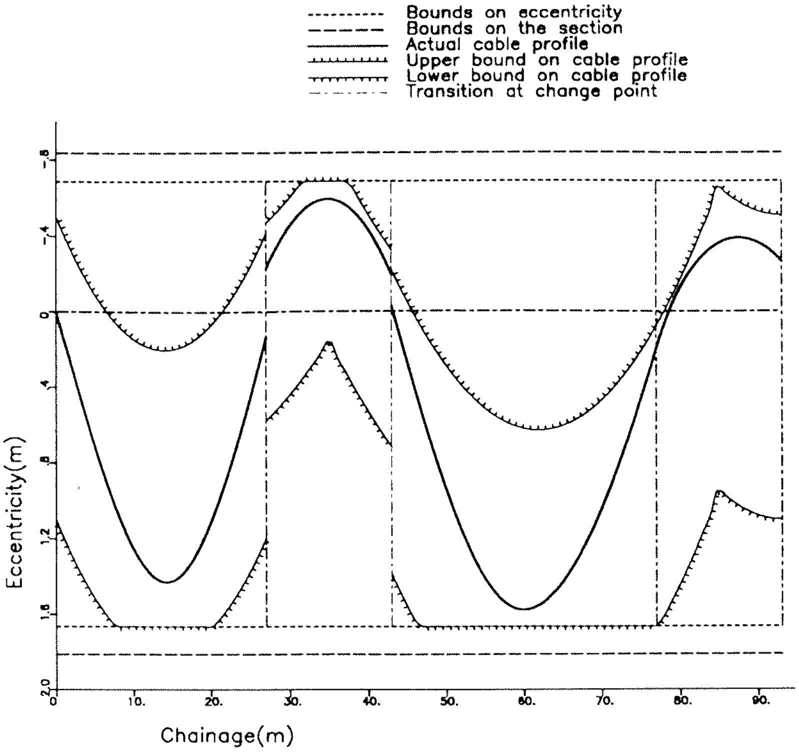

Figure 6. Typical plot of the cable profile at the end of second stage of construction

5 Human-Computer interaction

BRIDEX 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 system is 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 (making decisions and interpreting information). During a typical run, the following interactions take place between the designer and the expert system:

- The designer specifies the basic problem parameters - total span, widths, support positions, construction length at each stage and loading. These are normally part of the design brief specified by the client and there is little scope for variation.
- The designer selects the type of top flange (reinforced or prestressed), type of web (with or without ducts), web inclination, overall depth of the bridge, cantilever overhang and the quality of concrete.
- The system calculates the cross-section dimensions as discussed in section 4.2.1 and makes an initial estimate of the bottom flange thickness.
- The system analyses the structure to determine the live load moment envelopes and the dead load moments, taking account of the construction sequence.
- The designer chooses the desired amount of secondary moment at the service stage and at the initial transfer stage, by specifying the *reactant moment ratio* (RMR). The secondary moments are uniquely defined by their value at the internal supports, and most conveniently expressed as a fraction of the hogging bending moment at the supports due to the dead load of the structure.
- The system determines the limits on bottom flange thickness which it presents to the designer, who then chooses the actual dimensions.
- The system determines the limits on the prestress at critical sections, which it presents to the designer. The designer chooses the actual prestressing force to be applied, and positions at which cables over the piers are to be curtailed.
- The system calculates limits on the position and inclination of the cable anchorages, whose actual values are then fixed by the designer.
- The system calculates a suitable cable profile which satisfies the stress limits everywhere under both the initial transfer stage and working stage, and also generates the specified secondary moments as explained in section 4.2.3.
- Based on the Magnel diagram at each intermediate stage of construction, the system suggests the amount of prestress to be applied at that stage, which is then chosen by the designer. The system then works out the cable layout at that stage as explained in section 4.2.4.

6 Conclusion

The paper illustrates how good design principles can be developed by careful thought of the design process. By unravelling design intricacies and accounting for governing factors at an early stage of design process, the whole design evolves in a logical sequence. These design principles could be of immense help to students and designers.

Acknowledgements

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