Feature Report

Prestressed Concrete Design Using Spreadsheets

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Many practicing engineers are unaware of the potential offered by today's electronic spreadsheets. Since their introduction in 1978, along with word processors, they have been the most popular software purchased for use with microcomputers. It is estimated that in 1985, over 2 million spreadsheet programs were sold to microcomputer users.[1] Because this software was developed primarily as an accounting tool, it was not initially marketed toward the engineering profession. This is unfortunate, because in many instances electronic spreadsheets offer solution techniques that are superior to other more conventional forms of computerized analysis.

Initially, spreadsheets evolved as an alternative to the standard accountant's pad. Although the similarities between the balancing of a ledger and the solution of engineering equations might not be obvious, engineers are beginning to realize that spreadsheet concepts can be readily adapted to almost any manipulation of numerical data (for example, see Refs. 2, 3, 4, 5 and 6).

Spreadsheets can be designed to solve many engineering problems that may typically be programmed by using conventional languages such as FORTRAN, Pascal or BASIC. However, they do not simply offer alternatives to the more standard programming solutions, but in many instances offer superior features.

First of all, it is much easier to learn to use spreadsheets than to develop the skills necessary to program in higher level languages. Secondly, the most recent versions of the electronic spreadsheet have incorporated the use of what is referred to as "human access language" (considered by some to be a crude form of artificial intelligence), which allows users to enter simple English commands to accomplish tasks. The effect of this advancement, obviously, is that using the software is even easier to learn.

Perhaps the most overlooked benefit of spreadsheet technology in engineering applications is its easy adaptability to graphics. Throughout the course of time, engineers have been scratching out sketches of their ideas in the dirt or on the back of napkins. The latest spreadsheet technology allows users to change any of several parameters and instantly view a picture of the effect these changes have on a proposed solution. The ability to augment mathematical computations with graphics may be the single feature of most interest to practicing engineers.

The examples described herein demonstrate the adaptability of spreadsheets to the design of prestressed concrete. The computations are presented as an example of the types of problems that lend themselves easily to spreadsheets.

The authors' original intention in developing the spreadsheet application was to convey the possibilities that exist with this technique, as opposed to developing a full-blown production type program. However, due to the ease of implementing this design example of prestressed concrete beams to a spreadsheet, many more design features were incorporated than originally planned. The spreadsheet application would be of interest to any practicing engineer involved with prestressed concrete design.

SPREADSHEET FUNDAMENTALS

In recognition of the fact that many practicing engineers have not been exposed to spreadsheets, the following limited explanation and simple example should give the uninitiated a better understanding of how spreadsheets can be used to solve engineering problems. Those readers already versed in the fundamentals of spreadsheets may prefer advancing to the next section for the presentation of a more advanced application.

A spreadsheet is simply a matrix of cells in which data can be entered, manipulated and displayed. Each cell is identified by a column letter and a row numeral (e.g., A1, B3, etc.). Only a portion of the available spreadsheet is visible on the screen — the size of the viewing window is affected by the monitor type and video display adapter. However, the position of the viewing window can be moved with cursor control keys. The maximum spreadsheet size varies for different software vendors, but it typically is about 8000 rows by 250 columns.

To solve an engineering problem, one needs to design the spreadsheet to ac-

Synopsis

Electronic spreadsheets offer excellent opportunities for improving engineering calculations and designs. The built-in graphics capabilities they possess, coupled with the relative ease of designing spreadsheets, makes them a viable alternative to conventional programming. An example which demonstrates how a simple spreadsheet is set up and a more complex application for designing prestressed concrete beams are presented. The spreadsheet application presented is ideally suited to making preliminary design decisions quickly and efficiently, leading to better and more cost effective prestressed concrete designs.

```
E6:

                THERMAL BOW IN A WALL PANEL

      ----------------------------------------------------
      INPUT DATA:

                Wall Height          (ft)
                Wall Thickness       (in)
                Coeff. of Exp.       (in/in/F)
                Concrete Ec          (ksi)
                Temp. Diff.          (Far.)
      ----------------------------------------------------

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```

Fig. 1. Thermal bow example — Input screen.

commodate input data, governing equations, and displayed results. One of the most useful features of a spreadsheet is that after setting up the governing equations, any or all of the input data may be changed and the results will automatically be recalculated. This allows the user to perform a rapid sensitivity analysis and to iterate on design solutions. The recalculation is also extremely fast — virtually instantaneous for normal size spreadsheets, due in part to the use of assembly language by most spreadsheet developers. As a speed comparison, 5000 multiplications using one of the more popular spreadsheets took 10 seconds on an IBM PC. This same test took 16 seconds using interpretive BASIC on the same machine. While not as fast in performing calculations as a compiled language, overall efficiency — including program development and use — is where spreadsheets have an advantage.

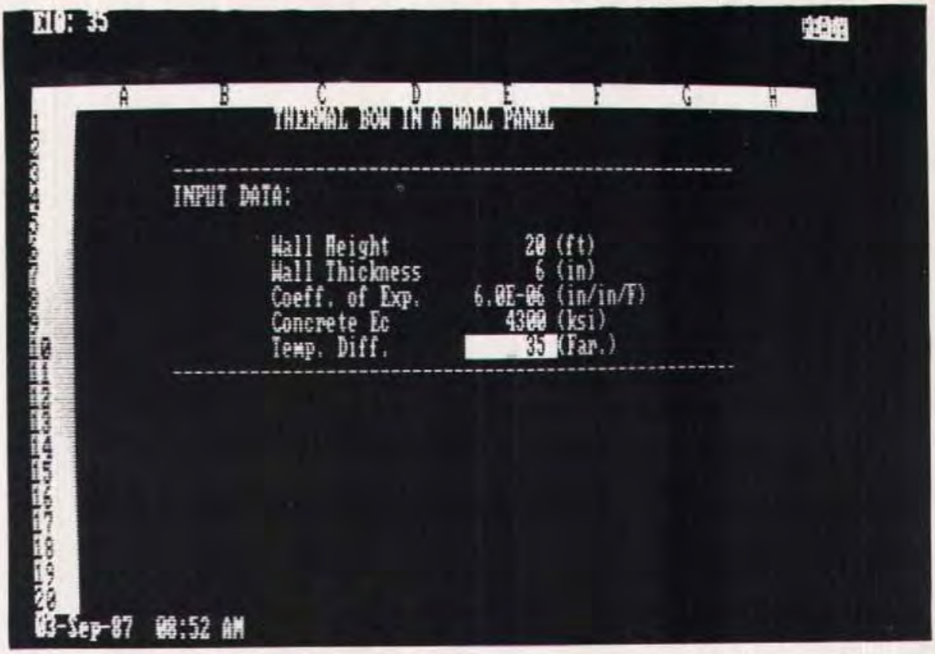
To illustrate the set up and use of a spreadsheet, the thermal bow in a wall panel will be calculated (see Section 3.2.2 of PCI Design Handbook.[7] The required input data are:

1. Wall height
2. Wall thickness
3. Thermal coefficient of expansion
4. Modulus of elasticity
5. Inside/outside daily temperature change

The desired results are:

1. Potential thermal bow for unrestrained wall
2. Force at midheight to restrain the bow
3. Wall panel stress caused by the restraint
4. Residual thermal bow

The input area is first set up in a portion of the spreadsheet as shown in Fig. 1. Text is entered by locating the cursor at a cell and entering the desired characters. Note that some of the text extends into the next column. If one of these overlapped cells was subse-



```
E10: 35

        A         B         C         D         E         F         G         H
 1                        THERMAL BOW IN A WALL PANEL
 2
 3          ----------------------------------------------------------
 4          INPUT DATA:
 5
 6                       Wall Height                 20 (ft)
 7                       Wall Thickness               6 (in)
 8                       Coeff. of Exp.         6.0E-06 (in/in/F)
 9                       Concrete Ec               4300 (ksi)
10                       Temp. Diff.                 35 (Far.)
11          ----------------------------------------------------------
12
13
14
15
16
17
18
19
20
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```

Fig. 2. Thermal bow example — Input data.

quently filled by an entry at that location, it would simply hide from view the extended portion of the text.

Setting up an input screen with a spreadsheet is much like using a word processing program. Unlike setting up an input screen with a conventional programming language, a spreadsheet allows the user to see the format of the display as it is being typed. Note that the cursor is positioned at the first data entry at Cell E6. Input values are entered by locating the cursor at the appropriate cell (E6-E10 in this case) and typing in the value. Fig. 2 shows the spreadsheet with a set of input data entered. Note that the format of the displayed data in a cell may be preset or changed such as Cell E8 was to scientific format with one decimal place.

The next step is to enter the appropriate equations to manipulate the input data for the desired results. The equations involve standard arithmetic operations plus a built-in library of functions similar to any other programming language. Descriptive text can also be provided to clearly note the intermediate results and the procedure used. The first calculation is for the thermal bow for an unrestrained wall. As outlined in the PCI Design Handbook,[7] the bow is equal to:

$$\text{Thermal Bow} = \frac{C \times \Delta T \times L^2}{8 \times h}$$

where

C = coefficient of thermal expansion
ΔT = inside/outside thermal differential
L = wall height
h = wall thickness

This equation is entered in spreadsheet cell E14 as shown in Fig. 3. Note that the equation is displayed on the top line of the screen and that the corresponding cell address for each variable in the equation is used. The (F2) in front of

```
E14: (F2) +E8*E10*(E6*12)^2/(8*E7)                          READY

                  THERMAL BOW IN A WALL PANEL

        ----------------------------------------------------
        INPUT DATA:

                 Wall Height               20 (ft)
                 Wall Thickness             6 (in)
                 Coeff. of Exp.       6.0E-06 (in/in/F)
                 Concrete Ec             4300 (ksi)
                 Temp. Diff.               35 (F)
        ---------------------------------------------------
        CALCULATIONS:

        Unrestrained thermal bow         0.25 (in)




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```

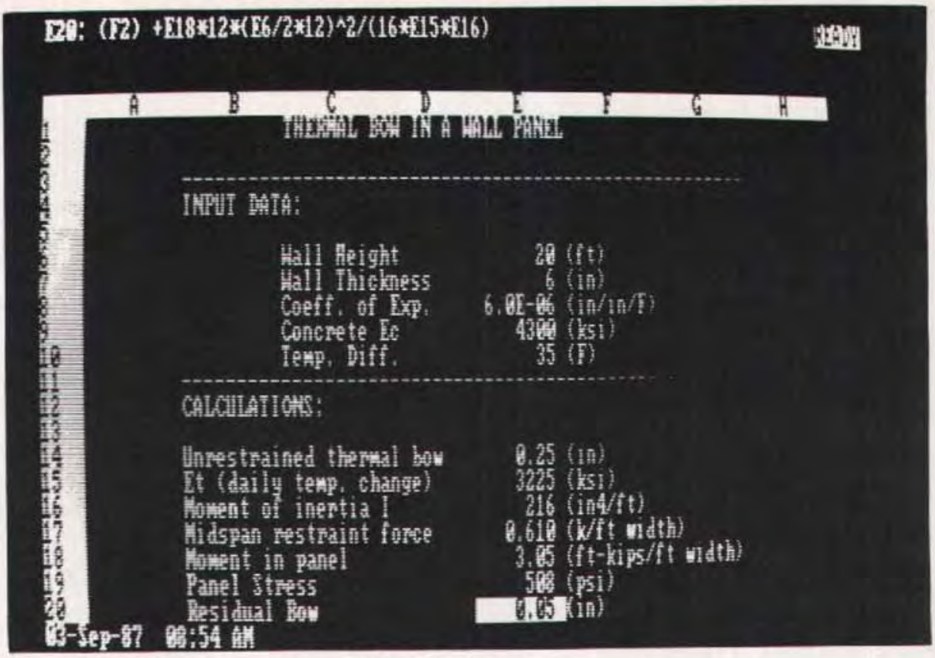
Fig. 3. Thermal bow example — Equation entry.

the equation indicates the result will be in fixed format with two decimal places. The unrestrained thermal bow of 0.25 in. (6.35 mm) is automatically tabulated as soon as the equation is entered into the cell. If one were to move the cursor to any one of the input data and key in a new value, the thermal bow would automatically be recalculated, with the spreadsheet substituting the current value of all the variables in the equation. Using the procedure outlined in the PCI Design Handbook, the remaining descriptive text and equations are entered in the spreadsheet as shown in Fig. 4. The contents of the cells for all of the equations are listed in Fig. 5.

One technique of interest to engineers accustomed to dealing with variable names (as opposed to cell addresses) is range naming. Any cell or group of cells can be assigned a name up to 15 characters long. This name may be used in place of the cell address in the equation. For example, by naming cells E6, E7, E8 and E10 as L, H, C and T, respectively, the equation in Cell E14 for the unrestrained thermal bow takes on the more meaningful form as shown at the top of Fig. 6. This technique is recommended for more complex spreadsheets and eliminates the need to keep track of cell addresses. It is also much easier to debug equations in this form.

Once the spreadsheet is set up as in this example, it may be saved and reused on any similar problem. It is extremely easy to adjust any input quantity and see the effect on the results almost instantaneously. The built-in graphics capabilities of most spreadsheets will be discussed in the more advanced application in the next section.

This simple example illustrates some of the advantages that spreadsheets have over conventional programming languages. One of the most time consuming programming tasks is dealing with input and output. This example clearly shows that spreadsheet



```
E20: (F2) +E18*12*(E6/2*12)^2/(16*E15*E16)                          READY

         A        B        C        D        E        F        G        H
                        THERMAL BOW IN A WALL PANEL

             -------------------------------------------------
             INPUT DATA:

                      Wall Height                  20 (ft)
                      Wall Thickness                6 (in)
                      Coeff. of Exp.          6.0E-06 (in/in/F)
                      Concrete Ec                4300 (ksi)
                      Temp. Diff.                  35 (F)
             -------------------------------------------------
             CALCULATIONS:

             Unrestrained thermal bow            0.25 (in)
             Et (daily temp. change)             3225 (ksi)
             Moment of inertia I                  216 (in4/ft)
             Midspan restraint force            0.610 (k/ft width)
             Moment in panel                     3.05 (ft-kips/ft width)
             Panel Stress                         508 (psi)
             Residual Bow                        0.05 (in)
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```

Fig. 4. Thermal bow example — Full spreadsheet.

```
E14: (F2) +E8*E10*(E6*12)^2/(8*E7)
E15: 0.75*E9
E16: 12*E7^3/12
E17: (F3) 48*E15*E16*E14/(E6*12)^3
E18: (F2) +E17*E6/4
E19: (F0) +E18*12000*E7/2/E16
E20: (F2) +E18*12*(E6/2*12)^2/(16*E15*E16)
```

Fig. 5. Thermal bow example — Spreadsheet equations.

"programming" is similar to working out a problem with a hand held calculator and a piece of paper. It is so easy that some unique problems that may not warrant taking the time to program conventionally are quickly handled using a spreadsheet.

A frequent criticism of spreadsheets is that they are good for simple problems, but are not as effective as conventional programming languages for solving more complex problems. However, even a fairly complex problem such as the one demonstrated in the next section is well within the capabilities of spreadsheets.

BACKGROUND FOR DESIGN APPLICATION

In the working stress design of prestressed concrete beams, three primary design parameters must be determined:

1. Section dimensions
2. Prestressing force
3. Tendon profile

```
E14: (F2) +C*T*(L*12)^2/(8*H)                                READY

            THERMAL BOW IN A WALL PANEL

     ---------------------------------------------
     INPUT DATA:

              Wall Height              20 (ft)
              Wall Thickness            6 (in)
              Coeff. of Exp.      6.0E-06 (in/in/F
              Concrete Ec            4300 (ksi)
              Temp. Diff.              35 (F)
     ---------------------------------------------
     CALCULATIONS:

     Unrestrained thermal bow        0.25 in

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```
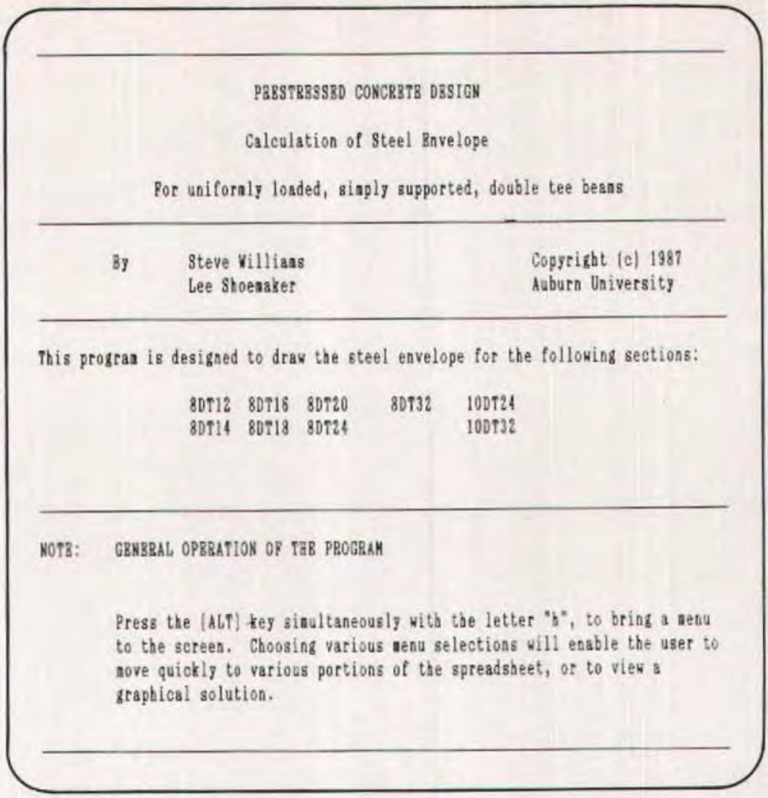

Fig. 6. Thermal bow example — Range naming.

These variables are interrelated and are further complicated by secondary design parameters, including concrete strength at transfer, concrete strength at service, type of steel (low relaxation or stress relieved), composite action, density of concrete, and shoring procedure. In addition to satisfying allowable stresses under service loads, cracking moment, ultimate moment, deflection, and shear calculations are required.

The power to change any design parameter and immediately see the effect on the results and the capability to instantly view the envelope of acceptable tendon profiles are the primary features of this spreadsheet that makes it so attractive as a prestressed concrete design tool. Most prestressed concrete design offices have computer facilities and programs available that are capable of sophisticated analyses. However, many of these programs are time consuming with regard to data input and are not usually conducive to design optimization — varying one or more parameters to realize possible cost or performance advantages. Hence, the ability to experiment with the sensitivity effects of various parameters is one reason spreadsheets are very effective teaching tools that are beginning to be utilized.[8,9]

The authors will demonstrate how a spreadsheet can easily be used in the design of prestressed concrete beams. This particular application has been developed for standard double tee sections, simply supported with uniform loads. The inclusion of other standard sections or sections with known properties could be accomplished in a matter of minutes, while other support and loading conditions would require somewhat more involved modifications. This method could provide a preliminary design tool for practicing engineers, after which a more rigorous analysis might be employed.



```
                  PRESTRESSED CONCRETE DESIGN

                  Calculation of Steel Envelope

        For uniformly loaded, simply supported, double tee beams

    By      Steve Williams                     Copyright (c) 1987
            Lee Shoemaker                      Auburn University

This program is designed to draw the steel envelope for the following sections:

            8DT12  8DT16  8DT20    8DT32   10DT24
            8DT14  8DT18  8DT24            10DT32

NOTE:   GENERAL OPERATION OF THE PROGRAM

        Press the [ALT] key simultaneously with the letter "h", to bring a menu
        to the screen.  Choosing various menu selections will enable the user to
        move quickly to various portions of the spreadsheet, or to view a
        graphical solution.
```

Fig. 7. Title screen.

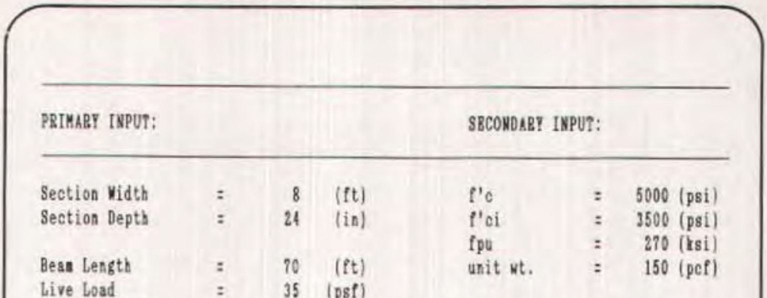
PRESTRESSED BEAM DESIGN APPLICATION

General — The "Title Screen" of the spreadsheet is shown in Fig. 7. This screen instructs the user to access a menu which expedites the viewing of various portions of the spreadsheet. The "Input Screen," which is the only screen designed for user changeable data, is shown in Fig. 8.

The input is divided into four categories as shown. Primary input includes design parameters that will vary frequently, and secondary input includes material data that will require less frequent modification. Composite input is self-explanatory, and strand input concerns design data with regard to the steel. All calculations performed within the spreadsheet are based on the input information on this screen.

The design procedure would involve entering a set of input data, or modifying a previous set, by moving the cursor to the item to be entered or changed. Properties of standard double tee sections have been set up in the spreadsheet and are automatically retrieved. After a trial section and supporting data are selected, the user presses a function key to view the tendon profile envelope for this data. Based on the state of the tendon profile, a user can then adjust any of the design parameters and again view the envelope.

After determining a design solution based on satisfying the working stresses along the length of the beam, the user can examine the ultimate and cracking



```
PRIMARY INPUT:                                  SECONDARY INPUT:

Section Width      :        8    (ft)           f'c          :     5000 (psi)
Section Depth      :       24    (in)           f'ci         :     3500 (psi)
                                                fpu          :      270 (ksi)
Beam Length        :       70    (ft)           unit wt.     :      150 (pcf)
Live Load          :       35   (psf)
Add. Dead Load     :       10   (psf)



COMPOSITE INPUT:                                STRAND INPUT:

Composite Topping  :    Y               Dia. (# of 16ths)    :        8
Shored ?           :    N               # of strands         :       12
f'c topping        :    3000   (psi)    Loss factor          :     0.89
Unit. wt. top.     :     150   (pcf)    stress-relieved ?    :        N
Thick. of top.     :       2    (in)    low-relaxation ?     :        Y
```

Fig. 8. Example input screen.

moment requirements of the ACI Code[10] and the estimated camber and deflection which is calculated using the method outlined in the PCI Design Handbook.[7] This information will allow the user to modify parameters if the envelope is too restrictive based on ultimate moment considerations, or to note the range of the envelope which should be used to achieve acceptable deflections.

In addition to the "Input Screen," the "Results Screen," and the graphic display of the "Tendon Profile Envelope," all intermediate calculations can be reviewed or printed to document the design problem. An example of this is shown in Fig. 9, which shows a partial envelope table that is used for a typical plot. The method used to calculate the envelope is taken from Naaman's book.[11]

The details of the formulas used in the cells of the spreadsheet and the spreadsheet technique that were used in this application are not presented. However, it is safe to say that most individuals could produce a spreadsheet tailored to his/her own needs within a very short time of being exposed to similar spreadsheet software. The design assumptions used in this spreadsheet application are included in the Appendix.

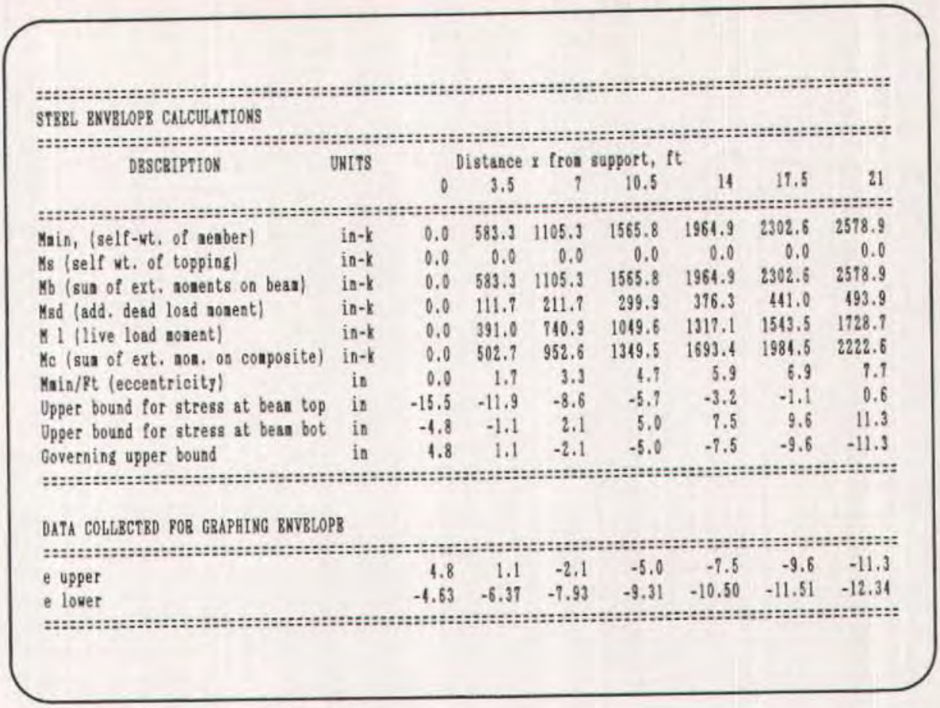
DESIGN EXAMPLE

The following example shows how this spreadsheet method can be used to design a prestressed concrete beam.

Objective: To design a prestressed double tee section.

Design Data:

Span = 35 ft (10.67m); simply supported.



```
=================================================================================
STEEL ENVELOPE CALCULATIONS
=================================================================================
        DESCRIPTION             UNITS            Distance x from support, ft
                                             0     3.5       7    10.5      14    17.5      21
=================================================================================
Mmin, (self-wt. of member)      in-k       0.0   583.3  1105.3  1565.8  1964.9  2302.6  2578.9
Ms (self wt. of topping)        in-k       0.0     0.0     0.0     0.0     0.0     0.0     0.0
Mb (sum of ext. moments on beam)  in-k     0.0   583.3  1105.3  1565.8  1964.9  2302.6  2578.9
Msd (add. dead load moment)     in-k       0.0   111.7   211.7   299.9   376.3   441.0   493.9
M l (live load moment)          in-k       0.0   391.0   740.9  1049.6  1317.1  1543.5  1728.7
Mc (sum of ext. mom. on composite) in-k    0.0   502.7   952.6  1349.5  1693.4  1984.5  2222.6
Mmin/Ft (eccentricity)           in        0.0     1.7     3.3     4.7     5.9     6.9     7.7
Upper bound for stress at beam top  in   -15.5   -11.9    -8.6    -5.7    -3.2    -1.1     0.6
Upper bound for stress at beam bot  in    -4.8    -1.1     2.1     5.0     7.5     9.6    11.3
Governing upper bound            in        4.8     1.1    -2.1    -5.0    -7.5    -9.6   -11.3
=================================================================================

DATA COLLECTED FOR GRAPHING ENVELOPE
=================================================================================
e upper                                    4.8     1.1    -2.1    -5.0    -7.5    -9.6   -11.3
e lower                                  -4.63   -6.37   -7.93   -9.31  -10.50  -11.51  -12.34
=================================================================================
```

Fig. 9. Partial envelope table data.

Live load = 50 psf (2.39 kPa)
Dead load = 10 psf (0.48 kPa)
(in addition to beam weight)

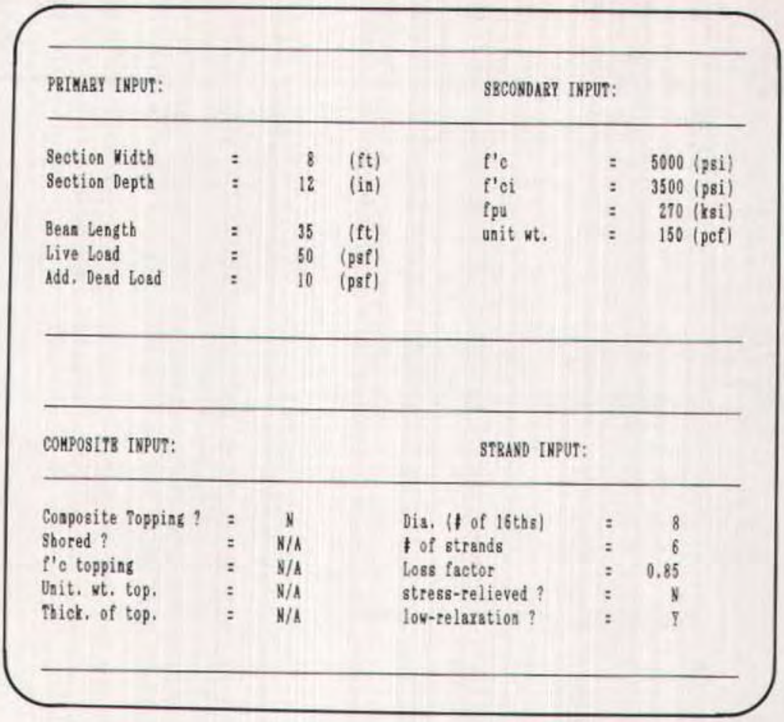
Step 1 — Determine reasonable section dimensions

The beam span and load data are entered under the primary input, along with a trial section, as shown in Fig. 10a. Other design data, most of which are set by standard material designations, are also entered and noted in Fig. 10a. After entering the data, the tendon profile envelope is displayed by pressing one key and is shown in Fig. 10c. The crossover of the upper and lower limits of the envelope indicates that the section is inadequate or that the concrete strength is inadequate for the chosen section.

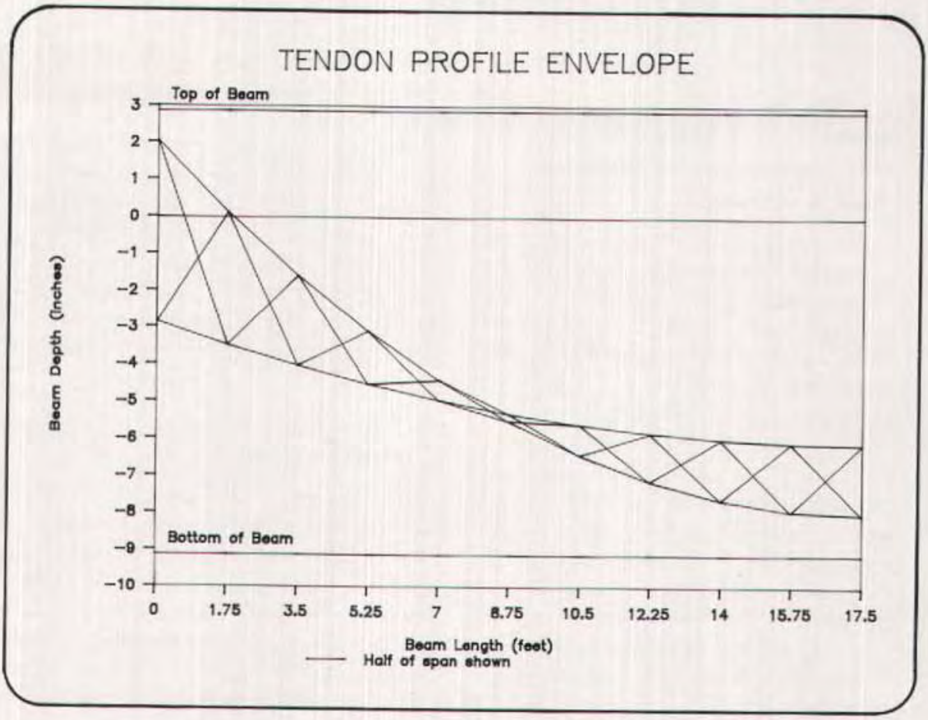
Any or all of these parameters may be adjusted to iterate on an acceptable section. For example, Fig. 11c shows an acceptable envelope for the next larger section (8DT14) and f'_{ci} increased from 3500 to 4000 psi (24 to 28 MPa). The need to increase f'_{ci} was evidenced by a slight crossover in the envelope near midspan. Fig. 12c shows another acceptable section (8DT16) with the original f'_{ci} of 3500 psi (24 MPa). Using this procedure, the designer obtains a reasonably shaped envelope that will accommodate straight, single-point depressed, or double-point depressed tendon arrangements in the next step.

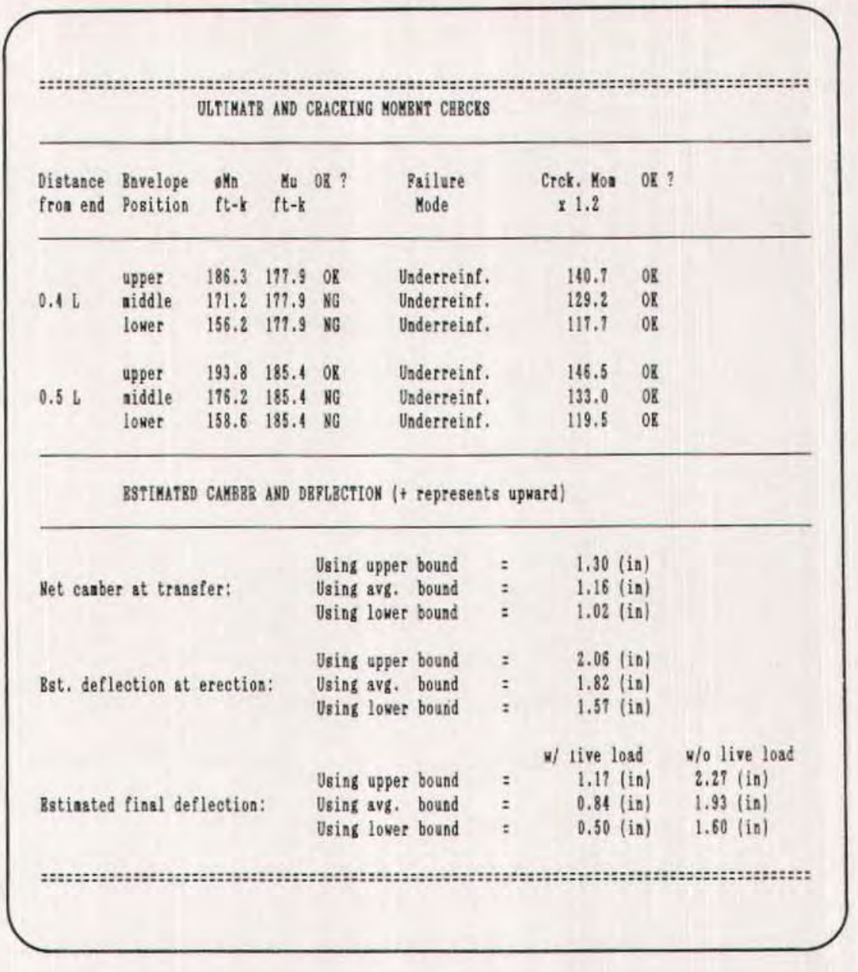
Step 2 — Adjustment of prestressing force

In this step, the designer is concerned with selecting the number and size of strands that will produce an envelope capable of accepting a standard tendon arrangement. This spreadsheet application does not address tendon arrangement, but the experienced designer should be able to select an arrangement



```
PRIMARY INPUT:                                 SECONDARY INPUT:

Section Width      :      8   (ft)             f'c          :   5000 (psi)
Section Depth      :     12   (in)             f'ci         :   3500 (psi)
                                               fpu          :    270 (ksi)
Beam Length        :     35   (ft)             unit wt.     :    150 (pcf)
Live Load          :     50   (psf)
Add. Dead Load     :     10   (psf)



COMPOSITE INPUT:                               STRAND INPUT:

Composite Topping ?  :    N          Dia. (# of 16ths)    :      8
Shored ?             :   N/A         # of strands         :      6
f'c topping          :   N/A         Loss factor          :   0.85
Unit. wt. top.       :   N/A         stress-relieved ?    :      N
Thick. of top.       :   N/A         low-relaxation ?     :      Y
```





```
==========================================================================================
                ULTIMATE AND CRACKING MOMENT CHECKS
------------------------------------------------------------------------------------------
Distance Envelope  øMn    Mu  OK ?        Failure        Crck. Mom   OK ?
from end Position  ft-k  ft-k              Mode            x 1.2
------------------------------------------------------------------------------------------

         upper    186.3 177.9  OK       Underreinf.        140.7     OK
0.4 L    middle   171.2 177.9  NG       Underreinf.        129.2     OK
         lower    156.2 177.9  NG       Underreinf.        117.7     OK

         upper    193.8 185.4  OK       Underreinf.        146.5     OK
0.5 L    middle   176.2 185.4  NG       Underreinf.        133.0     OK
         lower    158.6 185.4  NG       Underreinf.        119.5     OK
------------------------------------------------------------------------------------------

         ESTIMATED CAMBER AND DEFLECTION (+ represents upward)
------------------------------------------------------------------------------------------

                                Using upper bound    :      1.30 (in)
Net camber at transfer:         Using avg.  bound    :      1.16 (in)
                                Using lower bound    :      1.02 (in)

                                Using upper bound    :      2.06 (in)
Est. deflection at erection:    Using avg.  bound    :      1.82 (in)
                                Using lower bound    :      1.57 (in)

                                                       w/ live load   w/o live load
                                Using upper bound    :      1.17 (in)   2.27 (in)
Estimated final deflection:     Using avg.  bound    :      0.84 (in)   1.93 (in)
                                Using lower bound    :      0.50 (in)   1.60 (in)

==========================================================================================
```

Fig. 10a (top left). Design example Trial 1 — Input screen.

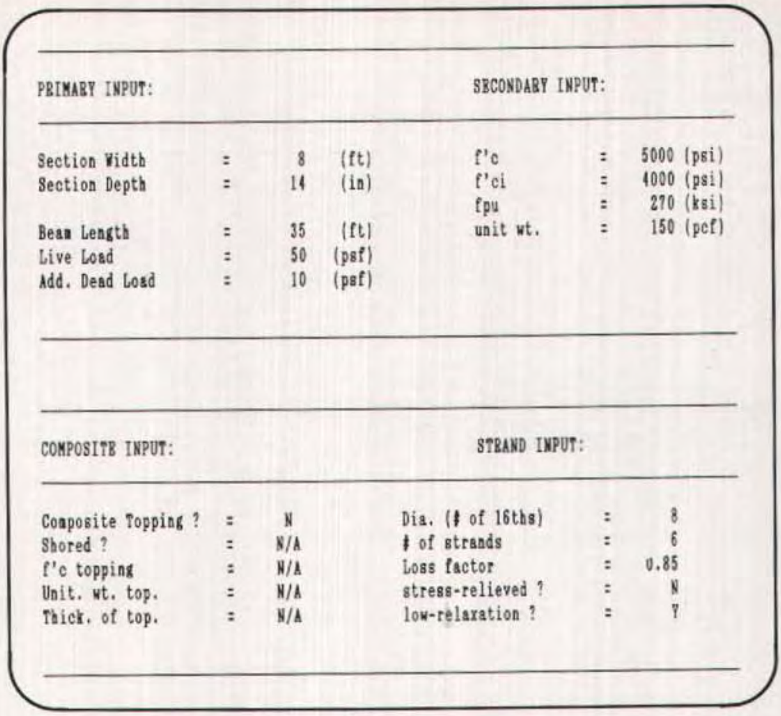
Fig. 10b (above). Design example Trial 1 — Results screen.

Fig. 10c (bottom left). Design example Trial 1 — Tendon profile envelope.

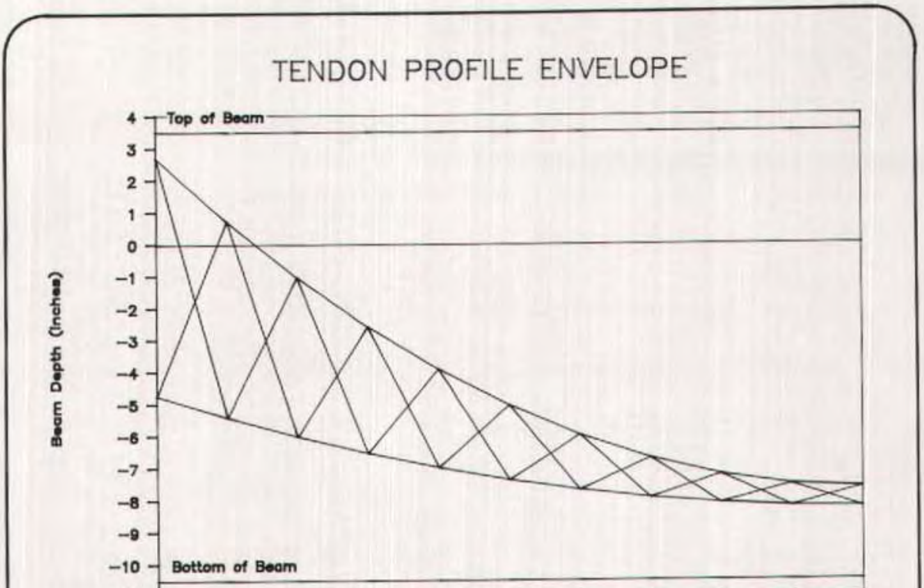
with a centroid that will fall within the desired region of the envelope. This is one area where the spreadsheet could be expanded: to accept standard tendon arrangements and calculate the location on the cross section that would fall within the envelope.

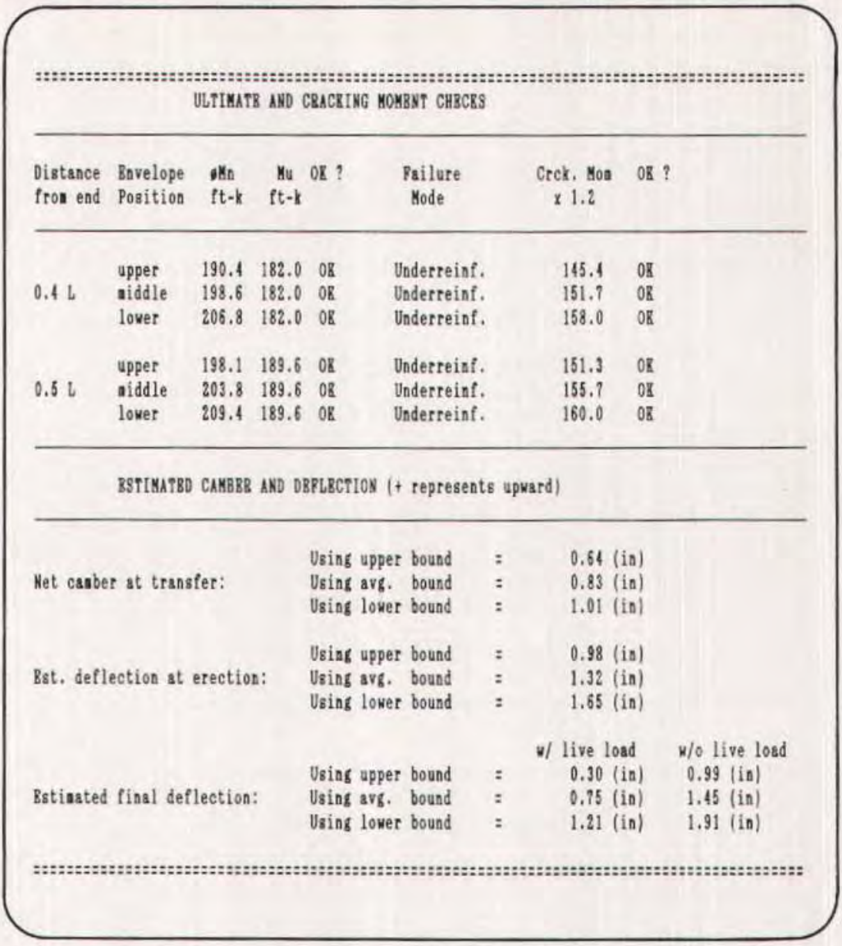
Step 3—Browse ultimate and cracking moment and estimated deflection

After adjusting the design parameters for an acceptable tendon profile envelope, the user can then browse the ul-



```
PRIMARY INPUT:                                SECONDARY INPUT:

Section Width       :      8    (ft)          f'c          :   5000 (psi)
Section Depth       :     14    (in)          f'ci         :   4000 (psi)
                                              fpu          :    270 (ksi)
Beam Length         :     35    (ft)          unit wt.     :    150 (pcf)
Live Load           :     50    (psf)
Add. Dead Load      :     10    (psf)



COMPOSITE INPUT:                              STRAND INPUT:

Composite Topping ? :    N            Dia. (# of 16ths)    :      8
Shored ?            :    N/A          # of strands         :      6
f'c topping         :    N/A          Loss factor          :   0.85
Unit. wt. top.      :    N/A          stress-relieved ?    :      N
Thick. of top.      :    N/A          low-relaxation ?     :      Y
```





```
=========================================================================================
                ULTIMATE AND CRACKING MOMENT CHECKS
-----------------------------------------------------------------------------------------

Distance  Envelope   øMn    Mu  OK ?       Failure          Crck. Mom   OK ?
from end  Position   ft-k   ft-k            Mode             x 1.2

-----------------------------------------------------------------------------------------

          upper     190.4  182.0  OK     Underreinf.          145.4     OK
0.4 L     middle    198.6  182.0  OK     Underreinf.          151.7     OK
          lower     206.8  182.0  OK     Underreinf.          158.0     OK

          upper     198.1  189.6  OK     Underreinf.          151.3     OK
0.5 L     middle    203.8  189.6  OK     Underreinf.          155.7     OK
          lower     209.4  189.6  OK     Underreinf.          160.0     OK

-----------------------------------------------------------------------------------------

          ESTIMATED CAMBER AND DEFLECTION (+ represents upward)

-----------------------------------------------------------------------------------------

                                 Using upper bound   :       0.64 (in)
Net camber at transfer:          Using avg.  bound   :       0.83 (in)
                                 Using lower bound   :       1.01 (in)

                                 Using upper bound   :       0.98 (in)
Est. deflection at erection:     Using avg.  bound   :       1.32 (in)
                                 Using lower bound   :       1.65 (in)

                                                          w/ live load    w/o live load
                                 Using upper bound   :       0.30 (in)     0.99 (in)
Estimated final deflection:      Using avg.  bound   :       0.75 (in)     1.45 (in)
                                 Using lower bound   :       1.21 (in)     1.91 (in)

=========================================================================================
```

Fig. 11a (top left). Design example Trial 2 — Input screen.

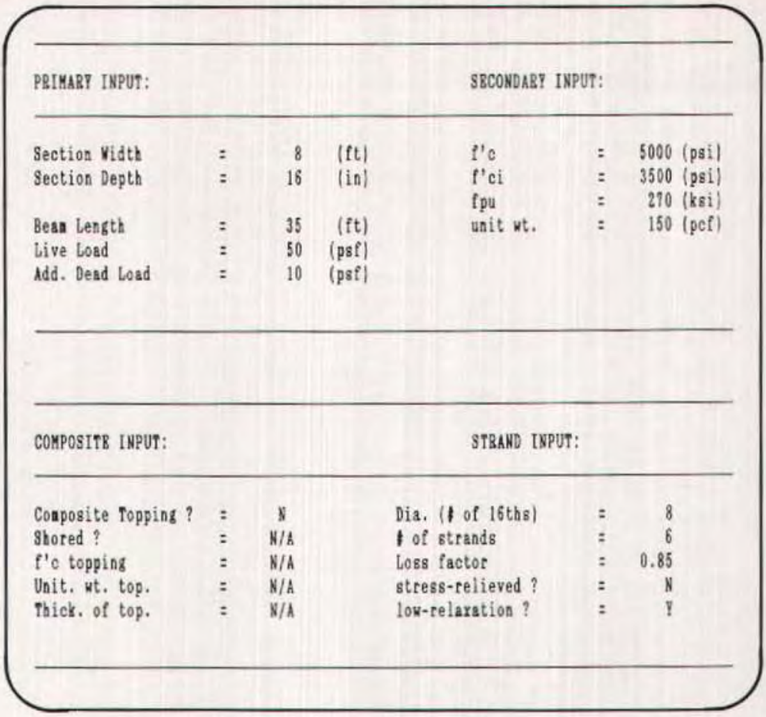
Fig. 11b (above). Design example Trial 2 — Results screen.

Fig. 11c (bottom left). Design example Trial 2 — Tendon profile envelope.

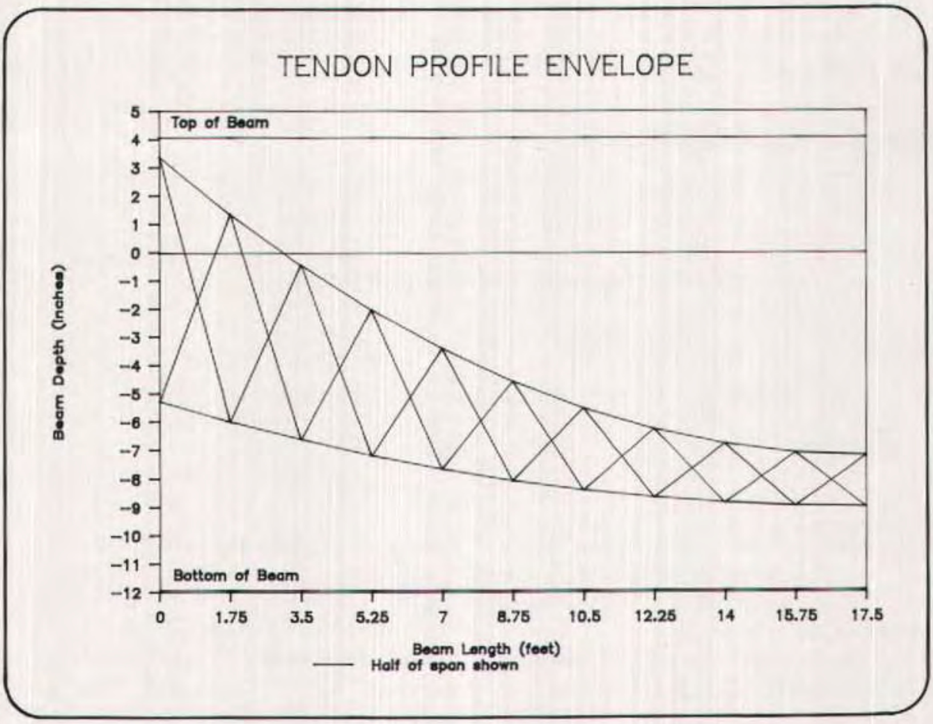
timate and cracking moment requirements as shown in Figs. 10b, 11b and 12b. The estimated deflections are also provided on these figures. If any of these results are not acceptable, design parameters may easily be readjusted accordingly.

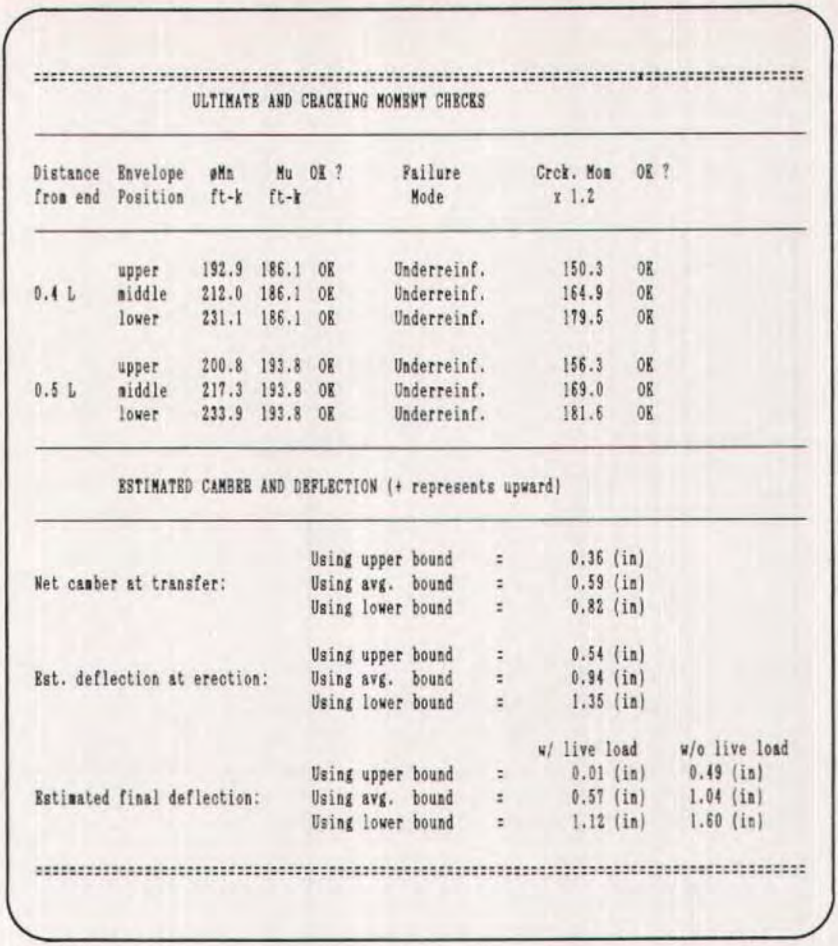
Design Example Summary

The important point in this design example is that the user may "flip" between the "Input Screen," "Results Screen," and "Tendon Profile Envelope" at the push of one key and in-



```
PRIMARY INPUT:                                  SECONDARY INPUT:

Section Width      :      8    (ft)             f'c          :   5000 (psi)
Section Depth      :     16    (in)             f'ci         :   3500 (psi)
                                                fpu          :    270 (ksi)
Beam Length        :     35    (ft)             unit wt.     :    150 (pcf)
Live Load          :     50    (psf)
Add. Dead Load     :     10    (psf)



COMPOSITE INPUT:                                STRAND INPUT:

Composite Topping ? :     N              Dia. (# of 16ths)      :      8
Shored ?            :    N/A             # of strands           :      6
f'c topping         :    N/A             Loss factor            :   0.85
Unit. wt. top.      :    N/A             stress-relieved ?      :      N
Thick. of top.      :    N/A             low-relaxation ?       :      Y
```





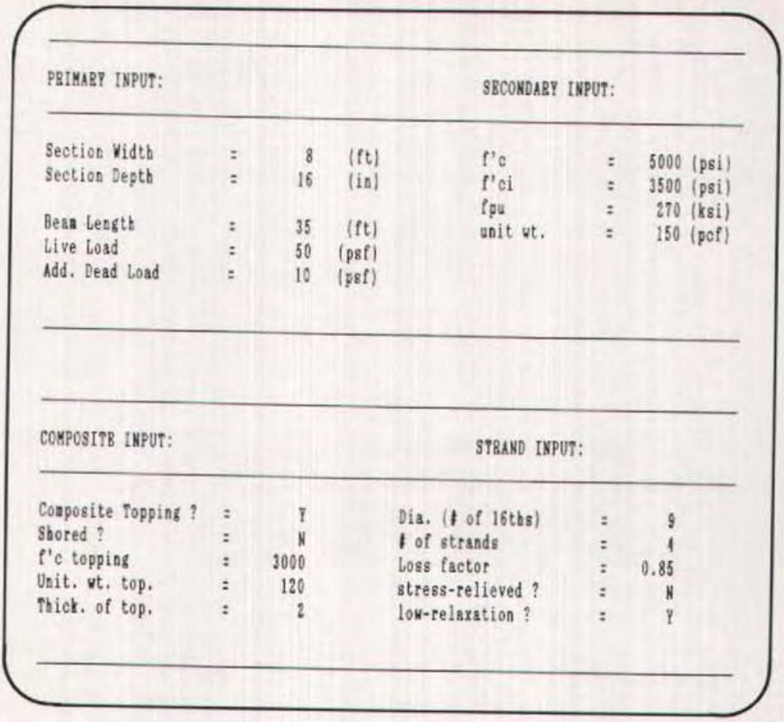
```
==========================================================================================
                 ULTIMATE AND CRACKING MOMENT CHECKS
------------------------------------------------------------------------------------------

Distance  Envelope   øMn     Mu  OK ?        Failure         Crck. Mom   OK ?
from end  Position   ft-k   ft-k              Mode             x 1.2
------------------------------------------------------------------------------------------

          upper     192.9  186.1  OK       Underreinf.        150.3     OK
0.4 L     middle    212.0  186.1  OK       Underreinf.        164.9     OK
          lower     231.1  186.1  OK       Underreinf.        179.5     OK

          upper     200.8  193.8  OK       Underreinf.        156.3     OK
0.5 L     middle    217.3  193.8  OK       Underreinf.        169.0     OK
          lower     233.9  193.8  OK       Underreinf.        181.6     OK
------------------------------------------------------------------------------------------

          ESTIMATED CAMBER AND DEFLECTION (+ represents upward)
------------------------------------------------------------------------------------------

                                Using upper bound     :        0.36 (in)
Net camber at transfer:         Using avg.  bound     :        0.59 (in)
                                Using lower bound     :        0.82 (in)

                                Using upper bound     :        0.54 (in)
Est. deflection at erection:    Using avg.  bound     :        0.94 (in)
                                Using lower bound     :        1.35 (in)

                                                          w/ live load     w/o live load
                                Using upper bound     :        0.01 (in)     0.49 (in)
Estimated final deflection:     Using avg.  bound     :        0.57 (in)     1.04 (in)
                                Using lower bound     :        1.12 (in)     1.60 (in)

==========================================================================================
```

Fig. 12a (top left). Design example Trial 3 — Input screen.

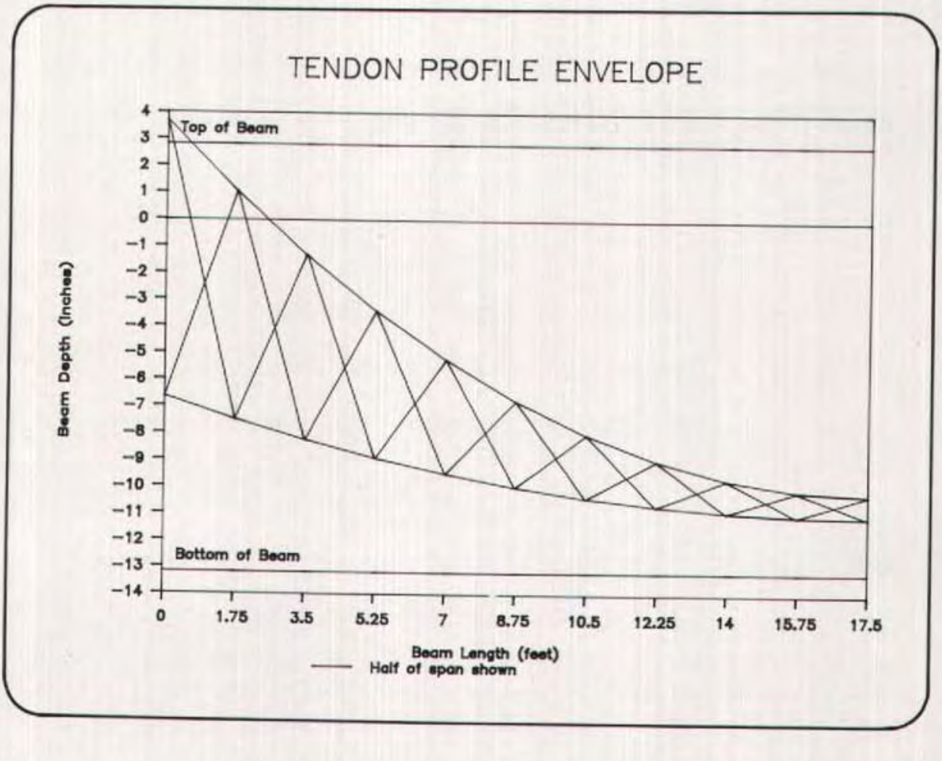
Fig. 12b (above). Design example Trial 3 — Results screen.

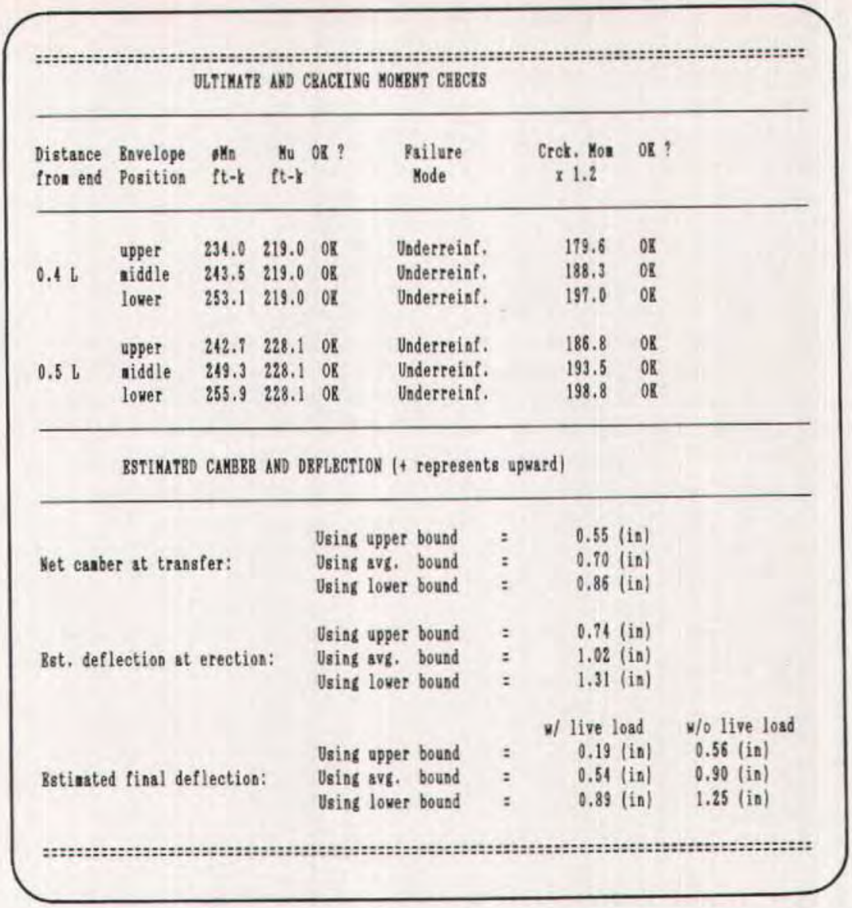
Fig. 12c (bottom left). Design example Trial 3 — Tendon profile envelope.

stantly see the effect of any changed design parameter. As a further example of this technique, Fig. 13 shows a composite section that also satisfies the design requirements. Composite design parameters such as unit weight of the topping, compressive strength of the topping, thickness of the topping, and shoring can readily be modified. Incorporating this many variables into design tables would be unwieldy, but it is easily handled in a spreadsheet format.



```
PRIMARY INPUT:                                      SECONDARY INPUT:

Section Width      :     8   (ft)             f'c          :   5000 (psi)
Section Depth      :    16   (in)             f'ci         :   3500 (psi)
                                              fpu          :    270 (ksi)
Beam Length        :    35   (ft)             unit wt.     :    150 (pcf)
Live Load          :    50   (psf)
Add. Dead Load     :    10   (psf)



COMPOSITE INPUT:                                    STRAND INPUT:

Composite Topping ? :     Y        Dia. (# of 16ths)      :      9
Shored ?            :     N        # of strands           :      4
f'c topping         :  3000        Loss factor            :   0.85
Unit. wt. top.      :   120        stress-relieved ?      :      N
Thick. of top.      :     2        low-relaxation ?       :      Y
```





```
==========================================================================================
                    ULTIMATE AND CRACKING MOMENT CHECKS
------------------------------------------------------------------------------------------
Distance Envelope  φMn    Mu  OK ?       Failure          Crck. Mom   OK ?
from end Position  ft-k  ft-k             Mode             x 1.2
------------------------------------------------------------------------------------------

         upper    234.0  219.0  OK     Underreinf.          179.6     OK
0.4 L    middle   243.5  219.0  OK     Underreinf.          188.3     OK
         lower    253.1  219.0  OK     Underreinf.          197.0     OK

         upper    242.7  228.1  OK     Underreinf.          186.8     OK
0.5 L    middle   249.3  228.1  OK     Underreinf.          193.5     OK
         lower    255.9  228.1  OK     Underreinf.          198.8     OK
------------------------------------------------------------------------------------------

         ESTIMATED CAMBER AND DEFLECTION (+ represents upward)
------------------------------------------------------------------------------------------

                                  Using upper bound    :       0.55 (in)
Net camber at transfer:           Using avg.  bound    :       0.70 (in)
                                  Using lower bound    :       0.86 (in)

                                  Using upper bound    :       0.74 (in)
Est. deflection at erection:      Using avg.  bound    :       1.02 (in)
                                  Using lower bound    :       1.31 (in)

                                                          w/ live load    w/o live load
                                  Using upper bound    :       0.19 (in)    0.56 (in)
Estimated final deflection:       Using avg.  bound    :       0.54 (in)    0.90 (in)
                                  Using lower bound    :       0.89 (in)    1.25 (in)

==========================================================================================
```

Fig. 13a (top left). Composite design example — Input screen.

Fig. 13b (above). Composite design example — Results screen.

Fig. 13c (bottom left). Composite design example — Tendon profile envelope..

CONCLUSION

It is important to note that this spreadsheet application was not developed with the intention of competing with existing computer programs. Many programs are available that will accomplish essentially the same tasks. However, the advantages that spreadsheets have to offer over more conventional programming languages are:

1. Spreadsheets can be developed without knowledge of common programming languages.
2. They offer superior input/output capabilities.
3. They can provide an instant "picture" of any graphical solution.

4. They are far more flexible than "canned" programs.
5. They can provide tremendous power through their capability to vary design parameters and allow quick sensitivity studies.

The spreadsheet application discussed here was created in a very short period of time (approximately 15 man-hours), yet in many ways is more powerful than some of the commercially available programs.

Every effort was made in the course of this paper to convey the potential that this spreadsheet approach offers as an engineering tool. However, the speed and efficiency that this method provides is only truly appreciated through its use. For example, a complete preliminary design similar to the one presented in this paper can be accomplished in a matter of minutes.

A traditionalist may argue that available design tables would provide a similar time saving method. However, design tables can only provide information specific to the parameters chosen in the development of the tables. Spreadsheets allow the user to change *any* parameter and instantly see the effect on the design.

The spreadsheet application presented shows the features of most interest to engineers in using this technique as a design tool. No matter how experienced the user is in prestressed concrete design, new insights into the behavior of prestressed beams will be developed using this method because a sensitivity analysis is so readily implemented. Because of the potential for a large productivity gain, engineers who make use of this technology will have time to investigate more design possibilities and create better, more cost effective designs.

* * *

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ACKNOWLEDGMENT

Sherrell Helm and Mike Armor of Southern Prestressed Concrete, Pensacola, Florida, reviewed the initial spreadsheet application and made valuable suggestions on improving the concept that were incorporated to make it a more useful tool for practicing designers. The cooperation and input of these practicing engineers was greatly appreciated by the authors.

APPENDIX — DESIGN ASSUMPTIONS

Tendon Profile Envelope

The allowable stresses used in obtaining the steel envelope are as follows:

Allowable tensile stress at transfer	$-3\sqrt{f'_{ci}}$
Allowable compressive stress at transfer	$0.6 f'_{ci}$
Allowable tensile stress at service	$-6\sqrt{f'_c}$
Allowable compressive stress at service	$0.45 f'_c$

Note that the increased allowable tensile stress at transfer within the end development length of the tendons and the increased allowable tensile stress at service in the precompressed tensile zones could be implemented in the spreadsheet if desired.

Strand Force

The jacking force in the tendons at transfer is assumed to be 70 and 75 percent of the ultimate strength of the strand for stress relieved and low relaxation, respectively. The force at transfer is assumed to be 90 percent of the jacking force.

Deflection Computations

Since the allowable stresses used were assumed below the modulus of rupture, uncracked sections were assumed in computing deflections. If the allowable tensile stresses are increased according to the ACI provisions,[10] a transformed cracked section and bilinear moment-deflection relations must be used in the deflection check. Long-term deflection multipliers were used from Fig. 4.6.3 of the PCI Design Handbook.[7] A parabolic tendon shape following the envelope is assumed.

Ultimate Strength Computations

For composite sections, the transformed width of the slab was assumed proportional to the compressive strengths of the concrete of the slab and precast beam. A strength reduction factor of 0.90 was used for sections that were under-reinforced according to Section 18.8.1 of the ACI Code, and a factor of 0.70 was used for over-reinforced sections. For over-reinforced sections, the nominal moment was calculated according to Section 18.8.2 of the ACI Code Commentary.

* * *

NOTE: Discussion of this article is invited. Please submit your comments to PCI Headquarters by December 1, 1988.