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Implementation of Prestress Loss Estimation Procedures

REPORT NO. 470.2

Fritz Engineering Laboratory

by

Ti Huang
Pennsylvania Department of Transportation Research Project 80-23

Lehigh University Research Project 470

Implementation of Prestress Loss Estimation Procedures

Report No. 470.1

A New Procedure for Estimation of Prestress Losses

by Ti Huang, May 1982

Report No. 470.2

Users Guide for Prestress Loss Estimation Procedures

by Ti Huang, December 1982
Two general procedures for the estimation of losses in prestressed concrete structural members are presented. Both are based on a rational analysis of the member, using experimentally established material characteristic equations. Both the computerized general procedure and the simplified manual procedure enable direct estimation of prestress loss at any specified time within the projected service life of the member. Detailed instructions are presented and several example problems are included to illustrate various features of the new procedure.

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Implementation of Prestress Loss Estimation Procedures

USERS' GUIDE FOR PRESTRESS LOSS ESTIMATION PROCEDURES

by

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ABSTRACT

Two general procedures for the estimation of losses in prestressed concrete structural members are presented. Both are based on a rational analysis of the member, using experimentally established material characteristic equations. Both the computerized general procedure and the simplified manual procedure enable direct estimation of prestress loss at any specified time within the projected service life of the member. Detailed instructions are presented and several example problems are included to illustrate various features of the new procedures.
I. INTRODUCTION

As the result of a series of research projects carried out over a period of fourteen years, two comprehensive procedures have been developed for the estimation of losses in prestressed concrete structural members. These procedures were rationally developed, based on long-term experimental observations on steel and concrete properties, and enable direct determination of prestress loss at any desired time during the service life of the structural member. Both are applicable to members of any fabrication and construction method, including pre-tensioned, post-tensioned, pre-post-tensioned and segmentally constructed.

The general estimation procedure directly applies the fundamental principles of mechanics and materials. It requires a large amount of computations, and is feasible only in a computerized environment. A computer program for this purpose developed by the researcher has been implemented by the Pennsylvania Department of Transportation. The computerized general procedure has also been incorporated by the Department's Prestressed Concrete Beam Program. Description of the computer program has been given in a previous project report (FL402.4). A brief flow diagram is given in Appendix B of this report. Chapter 3 contains detailed instructions on the usage of the computer program.

A simplified procedure, suitable for manual applications, has been proposed for consideration by the AASHTO Subcommittee on Bridges and Structures. The complete proposal, including the proposed amendment, commentary and background discussion, is previously given in Interim Report FL470.1. The amendment and commentary portions are reproduced in Appendix A of this report for the sake of convenience in referencing.
Chapter 2 provides detailed instructions for usage as well as illustrative example applications.
II. MANUAL PROCEDURE

2.1 General Discussion

The manual procedure (Appendix A) is based on the semi-logarithmic growth relationship, represented by Eq. (1). For any prestressing element $a_{sk}$, which is tensioned at concrete age of $t_{sk}$, the loss at any time is obtained by linear interpolation between an initial loss value of $IL$ at tensioning time $t_{sk}$, and a final loss value of $TL$ at the end of service life, which is taken at a concrete age of 100 years (36500 days).

The data needed for the application of the manual procedure includes the following:

Concrete material: Transfer strength, 28-day compression strength, and the loss characteristic (upper or lower bound)

Cross section: The complete geometrical description, including the area, centroidal location, and the moment of inertia.

Prestressing steel: For each increment of prestress, the area of steel, location, make and type of steel (stress-relieved or low relaxation), age of concrete when tensioned (and transferred), and the initial jacking stress.

In addition, for post-tensioned steel, also the profile and layout of tendon (both horizontally and vertically), coefficients of friction, wobble coefficient and the anchorage seating distance.

*For notations, see Appendix A.
Loading history: The complete fabrication and construction schedule of the structural member, including the magnitudes of moment increments and the time of application of each permanent load increment (such as distributed load for the deck slab and additional dead load caused by newly installed segments).

Two of the many loss components needed for loss estimations are obtained graphically. The initial relaxation loss of pretensioned steel, $\text{REL}_1$, is obtained from Fig. 1 (Appendix A), being controlled by the type of steel, the initial jacking stress and the time interval between pretensioning and transfer. The stress-independent component $\text{SRL}$ within the final loss is obtained from Fig. 2 (Appendix A), being dependent upon the selection of both steel and concrete materials, as well as the initial tensioning stress.

Most of the other loss components are dependent upon the stress increments $f_{sdi}$, $f_{c\ell i}$, and $f_{cgi}$, all of which are computed by means of the familiar elastic stress formula. The stress increments caused by the i-th stage* prestress and/or loading are:

$$f_{sdi} = a_{si} f_{pi} (-\frac{1}{A} - \frac{e_i e_k}{I}) \quad (2.1)$$

$$f_{c\ell i} = \frac{e_k}{M_{i I}} \quad (2.2)$$

$$f_{cgi} = \frac{e_k}{M_{g I I}} \quad (2.3)$$

*A stage refers to a time when a permanent change takes place in prestress, loading or both. See Appendix A, p. 54.
It should be pointed out that the cross-section resisting each increment of prestress and/or load should theoretically include all pretensioned steel and the post-tensioned steel which has been anchored in all previous stages. Consequently, the sectional properties A, I and e change from stage to stage. In most practical structural designs, however, these changes are very small, and it is quite satisfactory to ignore all effect of steel, and use the gross concrete section for all stress increment calculations.

If the i-th stage steel \( a_{si} \) is prestressed by post-tensioning, the stress \( f_{pi} \) in eq. (2.1) is the stress at the critical location under consideration immediately after anchoring. Therefore, the losses due to friction and anchorage seating has already taken place, and must be deducted from the initial jacking stress. Hence

\[
\frac{f_{pi}}{f_{pj}} = ACF
\]

(2.4a)

If \( a_{si} \) is a pre-tensioned element, the concrete prestress increments are most easily calculated by using the steel stress immediately before transfer, and the properties of the transformed cross section including the effects of \( a_{si} \) itself.

\[
\frac{f_{pi}}{f_{pj}} = REL_{t}
\]

(2.4b)

\[
\frac{f_{sdi}}{f_{pi}} = a_{si}f_{pi} \left( -\frac{1}{A} - \frac{e_{i}e_{k}}{I} \right)
\]

(2.1a)

In Eq. (2.1a), the subscript \( t \) refers to the transformed cross section.

Noting that the pre-transfer relaxation loss exists only in pre-tensioned steel, and the frictional and anchorage seating losses occur only in post-tensioned steel, equations (2.4a) and (2.4b) can be combined
into one single equation without ambiguity.

\[ f_{pi} = f_{pj} - \text{REL}_1 - ACF \quad (2.4) \]

In an earlier report (Fritz Laboratory Report 339.9)\(^{(5)}\), an alternate for eq. (2.1a) has been presented. The alternate equation uses the properties of the gross concrete section only, but introduces a new parameter as follows:

\[ f_{sdi} = a_{si} f_{pi} \left( - \frac{1}{A} - \frac{e_i e_k}{I} \right)_g \cdot \beta + n-1 \quad (2.1b) \]

where

\[ \beta = \frac{1}{a_{si} \left( \frac{1}{A} + \frac{e_i^2}{I} \right)_g} \quad (2.5) \]

In the above equations, the subscript \( g \) refers to the gross concrete section. It has been shown elsewhere\(^{(6)}\) that equations (2.1a) and (2.1b) are identical to each other, the difference is in the form only. The engineer is therefore free to choose the equation to use.
2.2 Suggested Calculation Procedure

To use the proposed manual procedure (Appendix A) for the estimation of prestress losses over the entire service life of the structural member, it is suggested that calculations follow the following sequence.

Step 1: Calculate the cross section properties: area, centroid and moment of inertia for each successive effective section.

Recognizing that at each prestressing stage, only a small effective area is added to the effective section, these calculations can be done in the following manner:

Given: \( A' \), \( y'_b \) and \( I' \) as the area, bottom centroidal distance and centroidal moment of inertia of a cross section. Let an additional effective area \( \Delta A \) be added at an eccentricity \( e' \).

Then: The new values for section properties are:

\[
\begin{align*}
A &= A' + \Delta A \\
\Delta e &= - \frac{(\Delta A) e'}{A} \\
e &= e' + \Delta e \\
y_b &= y'_b + \Delta e \\
I &= I' + (\Delta A) e'e
\end{align*}
\]

Step 2: Calculate all concrete stress increments

For the application of \( i \)th stage prestress and/or loading:

Calculate \( f_{pi} = f_{pj} - ACF - REL_1 \) \hspace{1cm} (2.4)
Calculate \( f_{sdi} = a_{si} f_{pl} \left( - \frac{1}{A} - \frac{e_i e_k}{I} \right) \) (2.1)

\[
f_{cgi} = M_{gi} \frac{e_k}{I}
\]

(2.2)

\[
f_{c\ell i} = M_{i} \frac{e_k}{I}
\]

(2.3)

These stress increments are needed for all prestressing elements whether tensioned before or after the \( i \)-th element in question. The section properties used are the ones including all steel elements up to but not including \( a_{si} \). The only exception is for a pretensioned steel, when the transformed section properties should be used. (See eq. 2.1a)

Step 2a: The calculation of ACF is used for post-tensioned steel only. First calculate the length over which the anchorage seating loss is distributed.

\[
k = K + \mu \frac{a}{x}
\]

\[
\ell_{a} = - \frac{1}{k} ln \left[ 1 - \sqrt{\frac{E_{s}}{f_{pj}}} \frac{a}{s} k \right]
\]

(4)

If \( \ell_{a} < x \)

\[
ACF = f_{pj} \left[ 1 - e^{-kx} \right]
\]

If \( \ell_{a} > x \)

\[
ACF = f_{pj} \left[ 1 - e^{-k(2\ell_{a} - x)} \right]
\]
If \( kx < 0.3 \), the calculations may be simplified

\[
\ell_a = \sqrt{\frac{E_a \Delta a}{k_f}}
\]

(6)

\[
ACF = f_{pj}(kx) \quad x > \ell_a
\]

\[
ACF = f_{pj}(k)(2\ell_a - x) \quad x < \ell_a
\]

Step 2b: The calculation of \( REL_1 \) is used for pretensioned steel only, and is taken from Fig. 1.

Step 2c: Use equations (2.1), (2.2) and (2.3) to calculate stress increments for each prestressing element, whether already anchored \((k<i)\), yet to be tensioned \((k>i)\), or is being tensioned \((k=i)\). A systematic way of recording these stress increments is recommended to avoid possible confusion.

Step 3: Calculate the prestress losses for each time interval. For any time interval between two consecutive stages of prestressing and/or loading, losses are to be calculated for each prestressing element which has already been anchored. Thus, for the time interval from \( t_{sm} \) to \( t_{sm}^{'}, \) (where \( m' = m + 1 \)), calculations are made for steel element \( a_{s1}, a_{s2}, \ldots, a_{sm} \). Detailed instructions are given in steps 4 through 7.
Step 4: Calculate the "initial loss" IL for prestressing steel element \( a_{sk} \) (tensioned at time \( t_{sk} \)):

If \( a_{sk} \) is a pre-tensioned element:

Obtain \( REL_1 \) from Fig. 1 (step 2b)

Calculate \[ ES = -n \sum_{i=k}^{m} f_{sdi} \]

\[ IL = REL_1 + ES \]

If \( a_{sk} \) is a post-tensioned element:

Obtain \( ACF \) from step 2a

Calculate \[ ES = -n \sum_{i=k+1}^{m} f_{sdi} \]

Calculate \[ GL = n \sum_{i=1}^{k} f_{cgi} \]

\[ IL = ES + ACF + GL \]

Step 5: Calculate the "final loss" at 100 years in prestressing element \( a_{sk} \)

Obtain SRL from Fig. 2

Calculate \[ S = C_s \log t_{sk} \]

where \( C_s = 4.0 \) for upper bound loss

\[ = 2.2 \] for lower bound loss
\[ \text{Calculate } CR = -1.2n \sum_{i=1}^{m} f_{sdi} \]

\[ \text{Calculate } CRA = -n \sum_{i=1}^{k-1} \left( 0.26f_{sdi} + 0.44f_{ci} \right) \log(t_{sk} - t_{si} + 1) \]

\[ \text{Calculate } LD = 2n \sum_{i=1}^{m} f_{ci} \]

\[ TL = IL + SRL - REL_1 - S + CR - CRA - LD \]

**Step 6:** The detailed calculations described in step 4 and 5 are needed for each prestressing steel element only for the first time interval after its tensioning (i.e., for \( m = k \)). For each subsequent time interval, adjustments for IL and TL can be calculated from the newly induced stress increments.

Let \( f_{sdm}' \) and \( f_{cm}' \) be the new stress increments in \( a_{sk} \) caused by the events at \( t_{sm}' \). Then

\[ \Delta IL = \Delta ES = -nf_{sdm}' \]

\[ \Delta TL = \Delta IL + \Delta CR - \Delta LD \]

\[ = -nf_{sdm}' - 1.2nf_{sdm}' - 2nf_{cm}' \]

**Step 7:** Calculate the partial loss at the beginning and end of the time interval:

At the beginning of time interval (\( t_{sm} \))

\[ PL_m = IL + (0.22)(TL - IL) \log(t_{sm} - t_{sk}) \]

At end of time interval (\( t_{sm}' \))

\[ PL_m' = IL + (0.22)(TL - IL) \log(t_{sm}' - t_{sk}) \]

At any other intermediate time (\( t \))

\[ PL = IL + (0.22)(TL - IL) \log(t - t_{sk}) \]
Step 8: Compare the partial loss \( PL \) calculated in Step 7 with that calculated for time \( t_{sm} \) at the end of the preceding time interval. Take the larger of the two values.

Step 9: For an individual prestressing element, the loss of prestress at any given time is \( PL \) from Step 8. The effective prestress remaining after losses is \( (f_{pj} - PL) \). The percentage loss is \( \left( \frac{PL}{f_{pj}} \right) \).

Step 10: If an overall indication including all prestressing elements is needed, calculations can be done as follows:

Total initial prestressing force \( F_i = \sum_{i=1}^{m} (a_{si} f_{pj}) \)

Total effective prestress force remaining \( F = \sum_{i=1}^{m} [a_{si} (f_{pj} - PL)] \)

Percentage loss of prestress = \( \left( \frac{F_i - F}{F_i} \right) \times 100\% \)

2.3 Example 1, A Pretensioned Member

The first illustrative example deals with a simple pretensioned I-girder. Such a member has only one prestressing "element" which includes all of the pretensioned strands. A second "stage" occurs at the time when the deck slab is cast, causing an increment of dead load stresses. The curb and parapet, and wearing surface constitute the third stage loading. The example is adapted from Example I of the 1975 AASHTO Interim Specifications for Bridges, Item 5(2). The given conditions are as follows:

Concrete material: Transfer strength \( f'_{ci} = 4000 \) psi
28-day strength \( f'_c = 5000 \) psi

Upper bound loss characteristics

Modular ratio \( n = 7 \)
Cross section: Illinois Standard 54 in. I-beam

Area \( A = 599 \text{ in.}^2 \)

Moment of inertia \( I = 213078 \text{ in.}^4 \)

Centroidal distances \( y_b = 24.97 \text{ in. from bottom} \)
\( y_t = 29.03 \text{ in. from top} \)

Weight \( w = 0.625 \text{ kips/ft.} \)

Span length \( \lambda = 70 \text{ ft.} \)

Prestressing steel: Sixteen \( \frac{1}{4} \text{ in.} \) 270 K stress-relieved strands

Area \( A_{ps} = 2.45 \text{ in.}^2 \)

Eccentricity \( e = 22.2 \text{ in.} \)

Jacking stress \( f_{pj} = 0.7 f' = 189 \text{ ksi} \)

Tensioning time: Transfer time is 2 days after tensioning \( t_{sl} = -2 \text{ days} \)

Loading history: At transfer, the member cambers up, activating the girder weight moment.

\( M_g = 382.8 \text{ kip-ft.} \)

At concrete age of 180 days, an 8 in. deck slab is cast. Each beam carries a slab width of 87 in.

\( M_\lambda = 446 \text{ kip-ft.} \)

At concrete age of 240 days, curb and parapet, and a 1\( \frac{1}{4} \)" asphalt wearing surface are added. These loads are resisted by the composite section including the slab.

\( M_{ws} = 83 \text{ kip-ft.} \)

Step 1: Section properties:

Stage 1: The transformed section properties, including pretensioned are needed.
The "added" area = (n-1)A_ps = (7-1)(2.45) = 14.7 in.²

\[ A_t = 599 + 14.7 = 614 \text{ in}^2 \]

\[ e_t = e - \frac{(\Delta A)e}{A_t} = 22.2 - \frac{14.7(22.2)}{614} = 22.2 - 0.53 = 21.67 \text{ in.} \]

\[ y_b = 24.97 - 0.53 = 24.44 \text{ in.} \]

\[ I = 213078 + 14.7(2.2)(21.67) = 220150 \text{ in.}^4 \]

Also, \( \beta = \frac{1}{2.45 \left( \frac{1}{599} + \frac{22.2^2}{213078} \right)} = 102.5 \)

Stage 3: For the composite section (from ref. 2)

\[ y_b = 40.9 \text{ in.} \]

\[ I = 530866 \text{ in.}^4 \]

Step 2: Calculation of concrete stress increments:

Stage 1: From Fig. 1 \((t_{s1} = -2, \text{ stress-relieved strands, } f_{pj} = 0.7f'_s)\)

\[ \text{REL}_1 = 0.025f'_s = 0.025 \times 270 = 6.75 \text{ ksi} \]

\[ f_{sd1} = -2.45(189 - 6.75) \left( \frac{1}{614} + \frac{21.67^2}{220150} \right) = -1.680 \text{ ksi} \]

Alternately,

\[ f_{sd1} = -2.45(189 - 6.75) \left( \frac{1}{599} + \frac{22.2^2}{213078} \right) \cdot \frac{102.5}{108.5} = -1.680 \text{ ksi} \]

\[ f_{cg1} = \frac{382.8(12)(21.67)}{220150} = 0.452 \text{ ksi} \]

Stage 2: \[ f_{cl2} = \frac{446(12)(21.67)}{220150} = 0.527 \text{ ksi} \]

Stage 3: \[ f_{cl3} = \frac{83(12)(38.13)}{530866} = 0.072 \text{ ksi} \]

Step 3a: Prestress losses for first time interval \((0 \leq t \leq 180)\)

(Step 4): \( \text{REL}_1 = 6.75 \text{ ksi} \)

\[ \text{ES} = -7(-1.680) = 11.76 \text{ ksi} \]

\[ \sigma_{IL} = \text{REL}_1 + \text{ES} = 18.5 \text{ ksi} \]
(Step 5): From Fig. 2 (upper bound loss, stress relieved strands, 
\( f_{pj} = 0.7f_s' \))

\[ SRL = 52.5 \text{ ksi} \]

\[ S = 0 \quad (t_{s1} = 0) \]

\[ CR = -1.2(7)(-1.680) = 14.11 \text{ ksi} \]

\[ CRA = 0 \]

\[ LD = 2(7)(0.452) = 6.33 \text{ ksi} \]

\[ \Delta TL = 18.5 + 52.5 - 6.75 - 0 + 14.11 - 0 - 6.33 = 72.0 \text{ ksi} \]

(Step 6): At \( t_{s2} = 180 \) days,

\[ PL = 18.5 + 0.22(72.0 - 18.5)\log_{180} = 18.5 + 26.5 = 45.0 \text{ ksi} \]

Step 3b: Prestress losses for second interval \((180 \leq t \leq 240)\)

\[ f_{sd2} = 0, \quad f_{cl2} = 0.527 \text{ ksi} \]

\[ \Delta IL = \Delta ES = 0 \]

\[ \Delta TL = -\Delta LD = -2(7)(0.527) = -7.38 \text{ ksi} \]

\[ IL = 18.5 \text{ ksi} \]

\[ TL = 72.0 - 7.38 = 64.6 \text{ ksi} \]

At \( t_{s2} = 180 \) days,

\[ PL = 18.5 + (0.22)(64.6 - 18.5)\log_{180} = 18.5 + 22.8 = 41.3 \text{ ksi} \]

At \( t_{s3} = 240 \) days,

\[ PL = 18.5 + (0.22)(64.6 - 18.5)\log_{240} = 18.5 + 24.1 = 42.6 \text{ ksi} \]

Note that both of the above values are lower than the 45.0 ksi value calculated for the end of the first interval. Hence, prestress loss should be taken as 45.0 ksi for the entire second time interval.

Step 3c: Prestress losses for third interval \((240 \leq t \leq 36500)\)

\[ f_{sd3} = 0, \quad f_{cl3} = 0.072 \text{ ksi} \]
\[ \Delta TL = -1(7)(0.072) = -1.01 \text{ ksi} \]

\[ s = 18.5 \text{ ksi} \]

\[ TL = 64.6 - 1.01 = 63.6 \text{ ksi} \]

At \( t_{s3} = 240 \text{ days} \),

\[ PL = 18.5 + (0.22)(63.6 - 18.5)\log_{10}240 = 18.5 + 23.6 = 42.1 \text{ ksi} \]

This is again lower than the previous value.

Equating \( PL \) at time \( t \) with the previous value of \( 45.0 \text{ ksi} \)

\[ 18.5 + (0.22)(63.6 - 18.5)\log_t = 45.0 \]

\[ t = 469 \]

Therefore, prestress loss will be taken as remaining constant until concrete age reaches 469 days.

**Discussion:** The computed ultimate loss of prestress, at a concrete age of 100 years, is 63.6 ksi, or 33.7 percent of the initial jacking stress. In contrast, the present AASHTO procedure yields a total loss of 38.7 ksi, or 20.5 percent. However, a direct comparison between these two sets of results is misleading, since the AASHTO procedure does not separate stresses caused by loading from prestress. In addition, the AASHTO procedure does not indicate a time for "all prestress losses" to take place, but is most probably referring to a much shorter time than the 100 years used in the proposed new procedure. The steel stress due to the gravity and other dead loads is

\[ 7(0.452 + 0.527 + 0.072) = 7.4 \text{ ksi} \]

Therefore, the "real" prestress loss predicted by AASHTO procedure is 38.7 + 7.4, or 46.1 ksi, or 24.4 percent. Using the linear relationship
of prestress loss growth, such a loss will be reached at time $t$ where

$$18.5 + (0.22)(63.6 - 18.5) \log t = 46.1$$

For the above equation, $t = 604$ days. In other words, the new procedure would predict a loss equivalent to the AASHTO prediction in less than two years, which is a short time, indeed.

Certain short cuts available to the proposed procedure should be pointed out. If only a "final loss" value is needed, the TL value for the third time interval can be calculated directly without any computation dealing with the prior time intervals. Also, noticing that $CRA$ and $S$ are both zero for post-tensioned tendons, and that $(IL - REL_1)$ is identical to $ES$,

$$TL = ES + CR + SRL - LD$$

This last equation is very similar to the current AASHTO equation, and the amount of work involved is also very similar.

2.4 Example 2, Post-Tensioned Member

The second illustrative problem deals with a simple post-tensioned beam. This problem is adapted from a design example in "Design of Prestressed Concrete Structures" by Lin and Burns (7). A T-shaped beam 96 ft. long is prestressed by four post-tensioning tendons. The cross-section dimensions and the locations of tendons are shown in Fig. 2-1. The given conditions are as follows:

Concrete material: Transfer strength $f'_c = 4000$ psi

28-day strength $f'_c = 4500$ psi

Upper bound loss characteristics

Modular ratio $n = 7$

Gross cross section properties: Area $A = 862$ in.$^2$

Centroidal distance $y_b = 29.81$ in.

$y_t = 22.19$ in.
Moment of inertia $I = 298260$ in.$^4$

Prestressing steel: Low relaxation VSL - multistrands

Two ES - 12 tendons, each containing 10-\(\frac{1}{2}\) in. strands

$a_s = 1.53$ in.$^2$ (Tendons A and D)

Diameter of rigid tube = 2-\(\frac{1}{2}\) in.

Two ES - 7 tendons, each containing 6-\(\frac{1}{2}\) in. strands

$a_s = 0.918$ in.$^2$ (Tendons B and C)

Diameter of rigid tube = 2 in.

Initial jacking stress $f_{pj} = 0.7 f'_s = 189$ ksi

Friction coefficient $\mu = 0.25$

Wobble coefficient $K = 0.0002$ per ft.

Anchorage seating distance $\Delta_a = 0.25$ in.

Modulus of elasticity $E_s = 28000$ ksi

Prestressing and loading sequence:

Stage 1: At $t_{s1} = 7$ days, Tendon A is post-tensioned. (The force from Tendon A is not sufficient to cause the beam to camber up. Consequently, the gravity load is not activated at this stage.)

Stage 2: At $t_{s2} = 10$ days, beam is lifted into position, supported over 95 ft. span.

$M_{g2} = 1060$ kip-ft.

Stage 3: At $t_{s3} = 40$ days, Tendons B and C are post-tensioned simultaneously.

Stage 4: At $t_{s4} = 42$ days, Tendon D is post-tensioned.

Stage 5: At $t_{s5} = 90$ days, wearing surface is cast.

$M_{g5} = 319$ kip-ft.

Prestress losses are to be determined for the mid-span section.
Step 1: Cross section properties:

Initially, the prestress force of Tendon A is resisted by the net concrete section, which is the gross section with the holes deducted. As successive tendons are anchored, the effective section increases. The relevant cross section properties are tabulated below.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Area (in²)</th>
<th>Yb (in)</th>
<th>Yt (in)</th>
<th>I (in⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Gross Section</td>
<td>862.0</td>
<td>29.81</td>
<td>22.19</td>
<td>298260</td>
</tr>
<tr>
<td>1</td>
<td>Net Section</td>
<td>845.9</td>
<td>30.30</td>
<td>21.70</td>
<td>287370</td>
</tr>
<tr>
<td>2</td>
<td>Add Tendon A</td>
<td>856.6</td>
<td>29.96</td>
<td>22.04</td>
<td>295250</td>
</tr>
<tr>
<td>3</td>
<td>Add B and C</td>
<td>869.5</td>
<td>29.56</td>
<td>22.44</td>
<td>304620</td>
</tr>
<tr>
<td>4</td>
<td>Add D</td>
<td>880.2</td>
<td>29.27</td>
<td>22.73</td>
<td>310000</td>
</tr>
</tbody>
</table>

Step 2: Concrete Stress Increments:

Stage 1: First, the ACF component for Tendon A is calculated according to Step 2a of Section 2.2.

\[ \alpha = \frac{4(32 - 3)}{96 \times 12} = 0.10069 \text{ rad.} \]

\[ k = K + \frac{\frac{\mu \alpha}{x}}{x} = 0.0002 + \frac{0.25(0.10069)}{48} \]

\[ = 0.000725 \text{ per ft.} = 0.0000604 \text{ per in.} \]

\[ \ell_a = -\frac{1}{k} \ell_n \left[1 - \sqrt{\frac{E_a \Delta a}{f_{pj}}} \right] = 802.3 \text{ in.} \]

\[ x = 48 \text{ ft.} = 576 \text{ in.} < \ell_a \]

\[ ACF = f_{pj} \left[1 - e^{-k(2\ell_a - x)} \right] = 189\left[1 - e^{-0.0000604(1605 - 576)} \right] \]

\[ = 11.4 \text{ ksi} \]
Prestress of Tendon A is resisted by the net concrete section (Section 1 in Step 1).

\[ f_{sd1} = 1.53(189 - 11.4) \left( -\frac{1}{845.9} - \frac{27.30 \, e_k}{287370} \right) \]

For Tendons A, B and C, and D, \( e_k = 27.30 \) in., 27.55 in., and 23.30 in., respectively. Therefore,

\[ f_{sd1} = -1.026 \, ksi, \quad -1.032 \, ksi, \quad \text{and} \quad -0.923 \, ksi, \text{respectively.} \]

(Even though Tendons B, C and D have not yet be tensioned, the corresponding \( f_{sd1} \) stresses are needed for evaluation of CR and CRA, see below.)

Stage 2: The gravity load moment \( M_{g2} \) is resisted by cross section 2. This moment is activated after Tendon A has been tensioned, but before Tendons B, C and D. Consequently, the corresponding concrete stress increment is \( f_{c2} \) for Tendon A, but \( f_{cg2} \) for the other tendons.

\[ f_{c2} \, f_{cg2} = \frac{1060(12)}{295250} \, e_k \]

\[ = 1.162 \, ksi, 1.172 \, ksi \text{ and } 0.989 \, ksi, \text{respectively.} \]

Stress increments at the other stages are calculated similarly. The results are tabulated in the following chart.
Stage Relevant Relevant Stress Tendons (ksi)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Relevance</th>
<th>Data</th>
<th>Stress Name</th>
<th>Tendons (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Section</td>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td></td>
<td>$a_{s1}$ = 1.53 in$^2$</td>
<td>$f_{sd1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ACF = 11.4 ksi</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td></td>
<td>$M_{g2}$ = 1060 k-ft</td>
<td>$f_{c2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$f_{c82}$</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td></td>
<td>$a_{s2}$ = 1.84 in$^2$</td>
<td>$f_{sd3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ACF = 8.43 ksi</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td></td>
<td>$a_{s4}$ = 1.53 in$^2$</td>
<td>$f_{sd4}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ACF = 11.8 ksi</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td></td>
<td>$M_{g5}$ = 319 k-ft</td>
<td>$f_{c85}$</td>
</tr>
</tbody>
</table>

Step 3a: Prestress losses in first interval ($7 \leq t \leq 10$ days). Only Tendon A is effective.

ACF = 11.4 ksi

ES = 0

GL = 0 (beam is not cambered up)

IL = ACF + ES + GL = 11.4 ksi

SRL = 43.5 ksi (from Fig. 2)

$S = 4 \log 7 = 3.4$ ksi

CR = $-1.2(7)(-1.026) = 8.62$ ksi

CRA = 0

LD = 0

TL = 11.4 + 43.5 - 3.4 + 8.62 - 0 - 0 = 60.1 ksi

At $t_{s2} = 10$ days,

PL = 11.4 + 0.22(60.1 - 11.4) log (10 - 7) = 16.5 ksi
Step 3b: Prestress loss in second interval \((10 \leq t \leq 40\) days). Only Tendon A is effective.

\[
\begin{align*}
& f_{sd2} = 0 \quad f_{ck2} = 1.162 \text{ksi} \\
& \Delta IL = \Delta ES = 0 \\
& \Delta TL = -\Delta LD = -2(7)(1.162) = -16.27 \text{ksi} \\
& TL = 60.1 - 16.3 = 43.8 \text{ksi} \\

& \text{At } t_{s2} = 10\text{ days}, \\
& PL = 11.4 + 0.22(43.8 - 11.4) \log (10 - 7) = 14.8 \text{ksi} < 16.5 \text{ksi} \\

& \text{At } t_{s3} = 40\text{ days}, \\
& PL = 11.4 + 0.22(43.8 - 11.4) \log (40 - 7) = 22.2 \text{ksi} \\
\end{align*}
\]

Step 3c: Prestress losses in third interval \((40 \leq t \leq 42\) days). For Tendon A:

\[
\begin{align*}
& f_{sd3} = -1.211, \quad f_{ck3} = 0 \\
& \Delta IL = \Delta ES = -7(-1.211) = 8.5 \text{ksi} \\
& \Delta TL = \Delta IL + \Delta CR = 8.5 - 1.2(7)(-1.211) = 18.7 \text{ksi} \\
& IL = 11.4 + 8.5 = 19.9 \text{ksi} \\
& TL = 43.8 + 18.7 = 62.5 \text{ksi} \\

& \text{At } t_{s3} = 40\text{ days}, \\
& PL = 19.9 + (0.22)(62.5 - 19.9) \log (40 - 7) = 34.1 \text{ksi} \\

& \text{At } t_{s4} = 42\text{ days}, \\
& PL = 19.9 + (0.22)(62.5 - 19.9) \log (42 - 7) = 34.4 \text{ksi} \\
\end{align*}
\]

For Tendons B and C:

\[
\begin{align*}
& ACF = 8.43 \text{ksi} \\
& ES = 0 \\
& GL = 7(1.172) = 8.21 \text{ksi} \\
& IL = 8.43 + 8.21 = 16.6 \text{ksi} \\
& SRL = 43.5 \text{ksi} \\
\end{align*}
\]
\[ S = 4 \log (40) = 6.4 \text{ ksi} \]
\[ CR = -1.2(7)(-1.032 - 1.219) = 18.9 \text{ ksi} \]
\[ CRA = -7\{0.26(-1.032) \log (40 - 7 + 1) + 0.44(+1.172) \log (40 - 10 + 1)\} \]
\[ = -2.5 \text{ ksi} \]
\[ LD = 2(7)(1.172) = 16.4 \text{ ksi} \]
\[ \Delta TL = 16.6 + 43.5 - 6.4 + 18.9 - (-2.5) - 16.4 = 58.7 \text{ ksi} \]

At \( t_{s4} = 42 \) days,
\[ \text{PL} = 16.6 + 0.22(58.7 - 16.6) \log (42 - 40) = 19.4 \text{ ksi} \]

Step 3d: Prestress losses for fourth interval \((42 \leq t \leq 90 \text{ days})\).

For Tendon A:
\[ f_{sd4} = -0.728 \text{ ksi} \]
\[ \Delta IL = \Delta ES = -7(-0.728) = 5.1 \text{ ksi} \]
\[ \Delta TL = \Delta IL + \Delta CR = 5.1 - 1.2(7)(-0.728) = 11.2 \text{ ksi} \]
\[ \Delta IL = 19.9 + 5.1 = 25.0 \text{ ksi} \]
\[ TL = 62.5 + 11.2 = 73.7 \text{ ksi} \]

At \( t_{s4} = 42 \) days,
\[ \text{PL} = 25.0 + 0.22(48.7) \log (42 - 7) = 41.5 \text{ ksi} \]

At \( t_{s5} = 90 \) days,
\[ \text{PL} = 25.0 + 0.22(48.7) \log (90 - 7) = 45.6 \text{ ksi} \]

For Tendons B and C:
\[ f_{sd4} = -0.732 \text{ ksi} \]
\[ \Delta IL = -7(-0.732) = 5.1 \text{ ksi} \]
\[ \Delta CR = -1.2(7)(-0.732) = 6.1 \text{ ksi} \]
\[ IL = 16.6 + 5.1 = 21.7 \text{ ksi} \]
\[ TL = 58.7 + 5.1 + 6.1 = 69.9 \text{ ksi} \]

At \( t_{s4} = 42 \) days,
\[ \text{PL} = 21.7 + 0.22(48.2) \log (42 - 40) = 24.9 \text{ ksi} \]
At $t_{s5} = 90$ days,

$$PL = 21.7 + 0.22(48.2) \log (90 - 40) = 39.7 \text{ksi}$$

For Tendon D:

$$ACF = 11.83 \text{ksi}$$

$$GL = n_{cg2} = 7(0.989) = 6.92 \text{ksi}$$

$$IL = 11.83 + 6.92 = 18.8 \text{ksi}$$

$$SRL = 43.5 \text{ksi}$$

$$S = 4 \log (42) = 6.5 \text{ksi}$$

$$CR = -1.2(7)(-0.923 - 1.089 - 0.666) = 22.5 \text{ksi}$$

$$CRA = -7(0.26(-0.923) \log 36 + 0.44(0.989) \log 33 + 0.26(-1.089) \log 3)$$

$$= -1.1 \text{ksi}$$

$$LD = 2(7)(0.989) = 13.8 \text{ksi}$$

$$TL = 18.8 + 43.5 - 6.5 + 22.5 - (-1.1) - 13.8 = 65.6 \text{ksi}$$

At $t_{s5} = 90$ days,

$$PL = 25.0 + 0.22(46.8) \log (90 - 42) = 43.7 \text{ksi}$$

For Tendons B and C:

$$f_{c25} = 0.328 \text{ksi}$$

$$\Delta LD = 2(7)(0.328) = 4.6 \text{ksi}$$

$$IL = 21.7 \text{ksi}$$

$$TL = 69.9 - 4.6 = 65.3 \text{ksi}$$

Step 3e: Prestress losses for fifth interval ($90 \leq t \leq 36500$). For

Tendon A: $f_{c25} = +0.324 \text{ksi}$

$$\Delta LD = 2(7)(0.324) = 4.5 \text{ksi}$$

$$IL = 25.0 \text{ksi}$$

$$TL = 73.7 - 4.5 = 69.2 \text{ksi}$$

At $t_{s5} = 90$ days,

$$PL = 25.0 + 0.22(44.2) \log (93) = 43.7 \text{ksi}$$

For Tendons B and C:

$f_{c25} = 0.328 \text{ksi}$

$$\Delta LD = 2(7)(0.328) = 4.6 \text{ksi}$$

$$IL = 21.7 \text{ksi}$$

$$TL = 69.9 - 4.6 = 65.3 \text{ksi}$$
At $t_{s5} = 90$ days,

$$PL = 21.7 + 0.22(43.6) \log 50 = 38.0 \text{ksi}$$

For Tendon D:

$$f_{c5} = 0.275 \text{ksi}$$

$$\Delta LD = 2(7)(0.275) = 3.9 \text{ksi}$$

$$IL = 18.8 \text{ksi}$$

$$TL = 65.6 - 3.9 = 61.7 \text{ksi}$$

At $t_{s5} = 90$ days,

$$PL = 18.8 + 0.22(42.9) \log 48 = 34.7 \text{ksi}$$

**Step 10:** The total loss of prestress at $t = 36500$

Total initial jacking force

$$= 1.53 \times 189 + 1.84 \times 189 + 1.53 \times 189 = 925 \text{k}$$

Final effective force after all losses

$$= 1.53(189 - 69.2) + 1.84(189 - 65.3) + 1.53(189 - 61.7) = 604 \text{k}$$

Total final loss

$$= 925 - 604 = 321 \text{k}$$

Percentage loss of prestress force

$$= \frac{321}{925} = 34.7\%$$

**Discussion:** The growth of prestress loss in each prestressing element is shown in Fig. 2-2. Also shown is a curve giving the total prestress force at any time.

It should be pointed out that the total initial jacking force of 925 kips is a fictitious quantity since at no time does that force act on either the prestressing steel or the concrete cross section. When Tendons B and C are stretched, Tendon A has already lost 22.2 ksi of prestress, or 34 kips of force. Similarly, at the time Tendon D is initially tensioned, the first three tendons have already suffered a total loss of 57.8 kips. On account of the staggered beginning time for each tendon, an average "loss of prestress" has
no meaning, and losses can only refer to total force.

As commented in Example 1, the results from the new procedures cannot be directly compared with the current AASHTO estimates because of its long assumed service life and because of the exclusion of direct load stresses. The calculated partial losses at the end of 20 years (in the fifth time interval) are 62.6 ksi, 59.1 ksi, and 55.2 ksi for the individual tendons. The total loss is prestressing force is 288 kips, or 31.1 percent of the initial 925 kip prestress force.

The direct stresses caused by gravity and additional dead loads in the tendons are 10.4 ksi, 10.5 ksi and 8.8 ksi respectively. Thus, the total force caused by loads is 48.7 kips. The total decrease of steel force is, therefore, 288 – 48.7 = 239 kips, or 25.8 percent of the initial 925 kip force.

2.5 Example 3, Post-Tensioned Member, Simplified Calculation

In this example, a variation of Example 2 is presented. Three modifications are made to the example in the previous section. First, the jacking forces for the tendons are increased to compensate for the losses due to friction and anchorage seating. Therefore, the given "initial" stress value of 0.7$f_s'$, or 189 ksi, is taken to represent the steel stress after ACF losses, or ($f_{pj}$ - ACF), at the mid-span section. Secondly, the calculation of concrete stress increments is simplified by using the gross section properties, neglecting the effects of the open ducts and anchored tendons. Thirdly, recognizing that the frictional effect is not large, the simpler equations in Step 2b are used to calculate ACF.

Examination of the equations of Section 2.2 reveals that all concrete stress increments, and consequently all loss components, can be calculated from the input value of ($f_{pj}$ - ACF). Determination of ACF is needed only as
a practical matter in order to control the tensioning of tendons. (It is impractical to measure the midspan steel stress for jacking control.) Also, as prestress loss is frequently represented as a percentage of the initial jacking stress, it is necessary to determine $f_{pj}$ to establish the basis of reference. Equations in Section 2.2 (Step 2b) show that the ACF loss is directly related to $f_{pj}$, but only indirectly to $(f_{pj} - ACF)$. A precise determination of ACF would require repeated trial and iteration. In this example, the ACF value determined in Example 2 is added to the desired $(f_{pj} - ACF)$ stress value of 189 ksi. The sum is then rounded into a practical value of $f_{pj}$. Subsequent calculations are based on this "rounded" value of $f_{pj}$. Thus, the desired stress value is met only approximately, but that is considered justifiable.

As only the given gross section properties will be used, the Step 1 calculations for other section properties are obviously not needed.

**Step 2: Concrete stress increments:**

**Stage 1:** Initial guess of ACF = 11.4 ksi (See Example 2).

- $f_{pj} = 189 + 11.4 = 200.4$ ksi (Use 200 ksi).
- $k = 0.0000604$ per in. (See Example 2).

\[ l_a = \sqrt{\frac{E_s A_s a}{F_{pj} k}} = \sqrt{\frac{28000(0.25)}{200(0.0000604)}} = 761.4 \text{ in.} > x \]

\[ AFC = f_{pj} k (2l_a - x) = 200(0.0000604)(1523 - 576) \]

\[ AFC = 11.4 \text{ ksi} \]

\[ f_{pj} - ACF = 188.6 \text{ ksi} \]

\[ f_{sdl} = 1.53(188.6) \left( \frac{1}{862} - \frac{26.81e_k}{298260} \right) \]
For $e_k = 26.81$ in., 27.06 in., and 22.81 in.,

$f_{sd1} = -1.030, -1.037, \text{ and } -0.927 \text{ ksi}$, respectively.

Stage 2: $f_{c2} = \frac{1060(12)}{298260} e_k = 1.143, 1.154, \text{ and } 0.973 \text{ ksi}$, respectively.

Stress increments for Stages 3, 4 and 5 are calculated in similar manner, the results are tabulated as follows:

<table>
<thead>
<tr>
<th>Stage</th>
<th>Relevant Data</th>
<th>Stress Increment</th>
<th>Tendons (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$f_{sd1}$</td>
<td>A</td>
</tr>
<tr>
<td>1</td>
<td>$f_{pj} = 200 \text{ ksi}$</td>
<td></td>
<td>-1.030</td>
</tr>
<tr>
<td></td>
<td>ACF = 11.4 \text{ ksi}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$M_{g2} = 1060 \text{ k-ft}$</td>
<td>$f_{c2}$</td>
<td>1.143</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$f_{cg2}$</td>
<td>1.154</td>
</tr>
<tr>
<td>3</td>
<td>$f_{pj} = 197 \text{ ksi}$</td>
<td>$f_{sd3}$</td>
<td>-1.244</td>
</tr>
<tr>
<td></td>
<td>ACF = 8.4 \text{ ksi}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$f_{pj} = 201 \text{ ksi}$</td>
<td>$f_{sd4}$</td>
<td>-0.929</td>
</tr>
<tr>
<td></td>
<td>ACF = 11.8 \text{ ksi}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>$M_{g5} = 319 \text{ k-ft}$</td>
<td>$f_{c5}$</td>
<td>0.344</td>
</tr>
</tbody>
</table>

Step 3: Prestress loss calculations:

Losses for each individual tendon at various times are calculated in the same fashion as in Example 2, out using the stress increments in the above table. The results are shown in the following table.
<table>
<thead>
<tr>
<th>State</th>
<th>Concrete Age</th>
<th>Tendon A (ksi)</th>
<th>Tendons B and C (ksi)</th>
<th>Tendon D (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1</td>
<td>7</td>
<td>11.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 2</td>
<td>10</td>
<td>16.5</td>
<td>(14.8)</td>
<td></td>
</tr>
<tr>
<td>Stage 3</td>
<td>40</td>
<td>22.4</td>
<td>34.6</td>
<td>16.5</td>
</tr>
<tr>
<td>Stage 4</td>
<td>42</td>
<td>34.8</td>
<td>44.0</td>
<td>19.4</td>
</tr>
<tr>
<td>Stage 5</td>
<td>90</td>
<td>48.2</td>
<td>(46.1)</td>
<td>41.9</td>
</tr>
<tr>
<td>End of Service Life</td>
<td>36500</td>
<td>72.9</td>
<td>68.6</td>
<td>63.1</td>
</tr>
</tbody>
</table>

| Jacking Stress | 200 | 197 | 201 |

Step 10: Total prestress losses:

The total initial jacking force $= \sum a_s f_{pj} = 976$ kips.

The total effective prestressing force at end of service life

$= \sum a_s (f_{pj} - TL) = 641$ kips

Total final loss of force $= 976 - 641 = 335$ kips.

Percentage loss of prestress force $= \frac{335}{976} = 34.3\%$.

Discussion: Comparison with Example 2 reveals that the simplifications invoked in this example has very little effect on the final percentage loss of prestress force. The two calculated results differ by only a little over 1 percent. While such good agreement cannot always be expected, there is certainly no doubt that these simplifications are indeed acceptable and practical.
In the design of post-tensioned members, a rather common practice is to specify the after anchorage steel stress \( f_{pj} - ACF \) and to depend on over-stretching to compensate the ACF losses. Under this condition, there is a tendency to base losses on the after anchorage stress instead of the initial jacking stress. This is not in agreement with the definition of prestress and losses, as defined in the proposed procedure (Appendix A). However, any attempt of comparison with other procedures must be done with this in mind. In the present example, if the specified stress of 189 ksi were taken as the base of reference, the total loss of prestress force would be 284 kips, or 30.7 percent of the initial force (925 kips). It is seen that a ten percentage difference resulted from the change of reference basis.

2.6 Example 4, Pre-Post-Tensioned Member

The fourth illustrative example is adapted from the design of a 103.1 ft. long beam on a Pennsylvania highway bridge\(^9\). The beam cross section is the PennDOT standard 26/63 I-beam, with dimensions and prestressing steels as shown in Fig. 2-3. All three post-tensioned tendons are draped in simple parabolic profiles. It is desired to calculate the prestress loss at mid-span section at a concrete age of 20 years.

**Concrete material:** Transfer strength \( f'_{ci} = 5000 \text{ psi} \)

28-day strength \( f'_{c} = 5750 \text{ psi} \)

Lower bound loss characteristics

Initial modular ratio \( n_i = 7 \)

Long term modular ratio \( n = 6.4 \)

**Gross cross section properties:** Area \( A = 1046 \text{ in.}^2 \)

Centroidal distance \( y_b = 30.975 \text{ in. from bottom} \)

\( y_t = 32.025 \text{ in. from top} \)

Moment of inertia \( I = 470081 \text{ in.}^4 \)
Prestressing steel: Pretensioned strands:

Forty-six 7/16 in. - 270 K stress-relieved strands

Six strands near top surface:
Area $a_{sa} = 0.69 \text{ in.}^2$
Eccentricity $e_a = -29.025 \text{ in.}$

Forty strands near bottom:
Area $a_{sb} = 4.60 \text{ in.}^2$
Eccentricity $e_b = 23.275 \text{ in.}$

(Total pretensioned strands $a_{sl} = 5.29 \text{ in.}^2$)
(Average eccentricity of all strands = 16.453 in.)

Jacking stress $f_{pj} = 0.7 f'_{s} = 189 \text{ ksi}$.
Tensioning time: $t_{sl} = -1 \text{ day}$ (Transfer at one day after tensioning.)

Post-tensioned tendons:

Three S/H 12-5 Stressteel multistrands of 270 K grade

Jacking stress varies to compensate for ACF losses, $(f_{pj} - ACF)$ at mid-span $= 163.4 \text{ ksi} = 0.605 f'_{s}$ (300 K force in each tendon).
Post-tensioning ducts are galvanized rigid tubing 2-5/8 in. in diameter.
Friction coefficient $\mu = 0.25$
Wobble coefficient $K = 0.0002 \text{ per ft.}$
Anchorage seating distance $\Delta_a = 3/16 \text{ in.}$
Modulus of elasticity $E_s = 28000 \text{ ksi}$.

Prestressing and loading sequence:

Stage 1: Transfer of pretensioned strand force one day after tensioning ($t_{sl} = -1 \text{ day}$). At this time, the beam
cambers up, activating the gravity load. $M_{g1} = 1447.73 \text{kip-ft.}$

Stage 2: At $t_{s2} = 2$ days, Tendon C is post-tensioned and anchored.

Stage 3: In the same day, Tendon B is post-tensioned and anchored.

Stage 4: Still in the same day, Tendon A is post-tensioned and anchored.

Stage 5: At $t_{s5} = 120$ days, an 8" deck slab is cast, together with diaphragms. The total moment due to the deck slab, formwork and diaphragm is $M_{\gamma5} = 1165.22 \text{ kip-ft.}$

Stage 6: At $t_{s6} = 180$ days, additional superimposed load (wearing surface) is added, $M_{\gamma6} = 279.03 \text{ kip-ft.}$ This moment is resisted by the composition section. (The effective flange slab is 7-1/2 in. thick and 84 in. wide, slab concrete strength is 3500 psi.)

As only the prestress loss after 20 years is required, it is not necessary to trace the entire history of prestress loss development. Only the one time interval which contains the time in question needs to be studied, and only those stress increments induced before or at the beginning of time interval are relevant. In the present example, the time in question falls in the sixth time interval following the sixth loading stage. Consequently, stress increments for all six stages are needed, but loss determination will be done only for the last time interval ($180 \leq t \leq 36500$).
### Step 1: Cross section properties:

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
<th>Area ((\text{in}^2))</th>
<th>(y_b) (in)</th>
<th>(y_t) (in)</th>
<th>(I) ((\text{in}^4))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Gross Section</td>
<td>1046</td>
<td>30.975</td>
<td>32.025</td>
<td>470081</td>
</tr>
<tr>
<td>1</td>
<td>Net Section (Deduct Duct Holes)</td>
<td>1030</td>
<td>31.33</td>
<td>31.67</td>
<td>461400</td>
</tr>
<tr>
<td>2</td>
<td>Initial Transformed (n_i = 7)</td>
<td>1062</td>
<td>30.83</td>
<td>32.17</td>
<td>479900</td>
</tr>
<tr>
<td>2a</td>
<td>Final Transformed (n = 6.4)</td>
<td>1058</td>
<td>30.88</td>
<td>32.12</td>
<td>478100</td>
</tr>
<tr>
<td>3</td>
<td>Add Tendon C</td>
<td>1070</td>
<td>30.68</td>
<td>32.32</td>
<td>482000</td>
</tr>
<tr>
<td>4</td>
<td>Add Tendon B</td>
<td>1082</td>
<td>30.43</td>
<td>32.57</td>
<td>487900</td>
</tr>
<tr>
<td>5</td>
<td>Add Tendon A</td>
<td>1094</td>
<td>30.15</td>
<td>32.85</td>
<td>496000</td>
</tr>
<tr>
<td>6</td>
<td>Composite Section Add Deck Slab</td>
<td>1585</td>
<td>41.50</td>
<td>21.50</td>
<td>952600</td>
</tr>
</tbody>
</table>

### Step 2: Concrete stress increments:

(See chart on following page.)
Step 2: Concrete stress increments:

<table>
<thead>
<tr>
<th>Stage</th>
<th>Section</th>
<th>Relevant Data</th>
<th>Stress</th>
<th>Steel Element</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Top Strands</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>$a_{s1} = 5.29 \text{ in}^2$</td>
<td>$f_{sd1}$</td>
<td>0.048</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\text{REL}_1 = 5.67 \text{ ksi}$</td>
<td>$f_{cgl}$</td>
<td>-1.056</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$M_{g1} = 1447.73 \text{ k-ft}$</td>
<td>$f_{pj}$</td>
<td>0.055</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$f_{ACF} = 8.61 \text{ ksi}$</td>
<td>$f_{sd2}$</td>
<td>0.133</td>
</tr>
<tr>
<td>2</td>
<td>2a</td>
<td>$a_{s2} = 1.84 \text{ in}^2$</td>
<td>$f_{sd3}$</td>
<td>0.204</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$f_{pj} = 177.1 \text{ ksi}$</td>
<td>$f_{sd4}$</td>
<td>-0.842</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$f_{ACF} = 8.44 \text{ ksi}$</td>
<td>$f_{cl5}$</td>
<td>-0.063</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>$M_{x5} = 1165.22 \text{ k-ft}$</td>
<td>$f_{cl6}$</td>
<td>-0.063</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>$M_{x6} = 279.03 \text{ k-ft}$</td>
<td>$f_{cl6}$</td>
<td>-0.063</td>
</tr>
</tbody>
</table>
Step 3: Prestress losses in the sixth time interval (m = 6).

Top strands (k = 1):

\( \text{REL}_1 = 5.67 \text{ ksi.} \)

\( \text{ES} = -7(0.048) - 6.4(0.055 + 0.133 + 0.204) \)
\( = -0.34 - 2.51 = -2.85 \text{ ksi} \)

\( \Delta \text{IL} = 5.67 - 2.85 = 2.8 \text{ ksi} \)

\( \text{SRL} = 39.0 \text{ ksi} \)
\( \text{S} = 0 \)

\( \text{CR} = -1.2(6.4)(0.048 + 0.055 + 0.133 + 0.204) \)
\( = -3.4 \text{ ksi} \)

\( \text{CRA} = 0 \)

\( \text{LD} = 2(6.4)(-1.056 - 0.842 - 0.063) = -25.1 \text{ ksi} \)

\( \Delta \text{TL} = 2.8 + 39.0 - 5.67 - 0 + (-3.4) - 0 - (-25.1) = 57.8 \text{ ksi} \)

At \( t = 20 \text{ years} = 7300 \text{ days}, \)

\( \text{PL} = 2.8 + 0.22(57.8 - 2.8) \log (7300) = 49.5 \text{ ksi} \)

Lower pretensioned strands (k = 1):

\( \text{REL}_1 = 5.67 \text{ ksi} \)

\( \text{ES} = -7(-1.673) - 6.4(-0.580 - 0.620 - 0.649) \)
\( = 11.71 + 11.83 = 23.54 \text{ ksi} \)

\( \Delta \text{IL} = 5.67 + 23.54 = 29.2 \text{ ksi} \)

\( \text{SRL} = 39.0 \text{ ksi} \)
\( \text{S} = 0 \)

\( \text{CR} = -1.2(6.4)(-1.673 - 0.580 - 0.620 - 0.649) = 27.0 \text{ ksi} \)

\( \text{CRA} = 0 \)

\( \text{LD} = 2(6.4)(0.837 + 0.632 + 0.119) = 20.3 \text{ ksi} \)

\( \Delta \text{TL} = 29.2 + 39.0 - 5.67 - 0 + 27.0 - 0 - 20.3 = 69.2 \text{ ksi} \)
At $t = 7300$ days,

$PL = 29.2 + (0.22)(69.2 - 29.2) \log(7300) = 63.2 \text{ ksi}$

Tendon C ($k = 2$):

$f_{pj} = 180.7 \text{ ksi} = 0.67f'_{p}$

$ACF = 8.61 \text{ ksi}$

$ES = -6.4(-0.551 - 0.570) = 7.17 \text{ ksi}$

$GL = 6.4(0.664) = 4.25 \text{ ksi}$

$\Delta IL = 8.61 + 7.17 + 4.25 = 20.0 \text{ ksi}$

$SRL = 37.0 \text{ ksi}$

$S = 2.2 \log(90) = 4.30 \text{ ksi}$

$CR = -1.2(6.4)(-1.515 - 0.522 - 0.551 - 0.570) = 24.25 \text{ ksi}$

$CRA = -(6.4)(0.26(-1.515) + 0.44(0.664)) \log(91) = 1.28 \text{ ksi}$

$LD = 2(6.4)(0.664 + 0.498 + 0.102) = 16.18 \text{ ksi}$

$\Delta TL = 20.0 + 37.0 - 4.30 + 24.25 - 1.28 - 16.18 = 59.5 \text{ ksi}$

At $t = 7300$ days,

$PL = 20.0 + (0.22)(59.5 - 20.0) \log(7300 - 90) = 53.5 \text{ ksi}$

Tendon B ($k = 3$):

$f_{pj} = 0.66f'_{p} = 177.1 \text{ ksi}$

$ACF = 8.44 \text{ ksi}$

$ES = -6.4(-0.640) = 4.10 \text{ ksi}$

$GL = 6.4(0.817) = 5.23 \text{ ksi}$

$\Delta IL = 8.44 + 4.10 + 5.23 = 17.8 \text{ ksi}$

$SRL = 35.0 \text{ ksi}$

$S = 2.2 \log(90) = 4.30 \text{ ksi}$

$CR = -1.2(6.4)(-1.655 - 0.574 - 0.612 - 0.640) = 26.73 \text{ ksi}$

$CRA = -(6.4)(0.26(-1.655) + 0.44(0.817)) \log(91) = 0.89 \text{ ksi}$

$LD = 2(6.4)(0.817 + 0.617 + 0.117) = 19.85 \text{ ksi}$
TL = 17.8 + 35.0 - 4.30 + 26.73 - 0.89 - 19.85 = 54.5 ksi
At t = 7300 days,
PL = 17.8 + 0.22(54.5 - 17.8)log(7300 - 90) = 48.9 ksi
Tendon A (k = 4):
\[ f_{pj} = 0.64 f_s = 172.0 \text{ ksi} \]
ACF = 8.12 ksi
ES = 0
GL = 6.4(0.971) = 6.21 ksi
IL = 8.12 + 0 + 6.21 = 14.3 ksi
SRL = 34.0 ksi
S = 2.2 log (90) = 4.30 ksi
CR = -1.2(6.4)(-1.795 - 0.625 - 0.674 - 0.709) = 29.21 ksi
CRA = -6.4(0.26(-1.795) + 0.44(0.971)log(91) = 0.49 ksi
LD = 2(6.4)(0.971 + 0.737 + 0.132) = 23.55 ksi
TL = 14.3 + 34.0 - 4.30 + 29.21 - 0.49 - 23.55 = 49.2 ksi
At t = 7300 days,
PL = 14.3 + 0.22(49.2 - 14.3)log(7300 - 90) = 43.9 ksi

Step 10: Total prestress loss:
Initial prestressing force \( F_i = 0.69(189) + 4.60(189) + 1.84(180.7) + 1.84(177.1) + 1.84(172.0) = 1975 \text{ kips} \)
Effective prestress force remaining after 20 years
\[ F = 0.69(189 - 49.5) + 4.60(189 - 63.2) + 1.84(180.7 - 53.5) + 1.84(177.1 - 48.9) + 1.84(172.0 - 43.9) = 1381 \text{ kips} \]
Percentage loss = \( \frac{1975 - 1381}{1975} = 30.1\% \)
Percentage loss for pretensioned strands = \( \frac{325}{1000} = 32.5\% \)
Percentage loss for post-tensioned tendons = \( \frac{269}{975} = 27.6\% \)
**Discussion:** Two special features of the new procedure are demonstrated in this example. The prestress losses are calculated directly for the sixth time interval, without any need for loss information in the five prior intervals. The work involved here is not very much different from that required for prestress loss determination in the first time interval, as demonstrated in the other examples, except that more concrete stress increments are included. This capability of directly determining the prestress loss at a specified time is one of the major advantages of the new procedure. Most of the current procedures, such as the AASHTO Bridge Specification method (1,2), do not contain time as a varying parameter. Consequently, it is not possible to distinguish prestress losses at different times. Only one value referring to an undefined "time after all losses have taken place" is calculated. On the other hand, the few methods which do include a time parameter, such as the PCI method (8), generally require summation of prestress losses from each time interval. The new procedure is unique in its ability to determine prestress loss at any specified time directly without summation.

The pretensioned strands are treated as two separate "elements" in recognition of their diverse locations. The six top strands are placed 3 inches from the top. The other 40 strands are arranged in several layers from 2 to 14 inches from the bottom, the centroid of this group being 7.7 inches from the bottom, or 55.3 inches from the top. The centroid of all forty-six strands is located 16.473 inches below the gross-section centroidal axis, or 14.522 inches from the bottom. It falls in the region of the beam between the two groups of pretensioning strands. It is felt unreasonable to expect that the behavior of the strands in either group should be closely related to the concrete stresses at such an outside "average" location. Consequently, the two groups of pretensioned strands are treated separately, as two steel elements, $a_{sa}$ and
asb' tensioned at the same time. In Step 2, separate stress increments are calculated at the centroid of each group. It is seen that they carry opposite signs in every stage, thus confirming that the two groups of strands behave very differently. The estimated 20-year loss in the top strands is nearly 20 percent lower than that in the lower strands.

The original design calculations (9), from which this example was adapted, were based on the PennDOT Design Manual effective at that time (10). Losses were separately calculated for the pretensioned and post-tensioned steel elements. For the pretensioned strands, the estimated total loss was 61.1 ksi, or 32.3 percent of the jacking stress. For the post-tensioned tendons, the estimated total loss was 37.9 ksi, or 23.2 percent of the initial "after seating" stress (163.4 ksi). Again, it should be pointed out that the loss value here for post-tensioned tendons does not include the ACF losses, as well as ES components for Tendons B and A, which are all included in the calculations by the new procedure. When adjusted to the same basis, the two sets of estimates, one by the PennDOT Design Manual, the other by the new procedure, agreed rather well. In fact, both the AASHTO and the PennDOT procedures generally yield loss estimates comparable to those by the new procedure at concrete age of 20 years, provided that the lower bound loss characteristics are used.

One additional point in the illustrative calculations deserves some discussion. In the calculation of ES, appropriate modular ratio is used for each stress increments, dependent upon the age of concrete when the increment is applied. On the other hand, CR and LD are long term effects, and is controlled by the prevailing concrete property over the entire time range under consideration. Consequently, only the long term modular ratio 6.4 is used in the example calculations for these components.
Fig. 2-1  Post-Tensioned Member, Examples 2 and 3
Fig. 2-3 Pre-Post-Tensioned Member, Example 4
III. COMPUTER PROCEDURE

3.1 General Description

The computerized general procedure directly applies the basic principles of mechanics and materials. The experimentally established stress-strain-time relationships of concrete and steel materials are combined with the mechanical requirements of equilibrium and compatibility. The stress and strain distributions in a given prestressed concrete bridge member are then determined before and after each increment of prestress and/or loading, as well as a series of pre-selected concrete ages covering the entire assumed service life (100 years) of the member. In Appendix B is a brief flow diagram of the computer program FOUR02, which has been incorporated into the PennDOT general prestressed concrete beam design program.

In comparison with the manual procedure described and illustrated in the previous chapter, the computerized procedure has certain advantages and certain disadvantages. The calculations are automated, hence less susceptible to human calculation errors. The fundamental principles are used, and the transition at each prestressing or loading stage is more smoothly indicated. On the other hand, the requirement of a fixed program necessitated a number of restrictions and limitations. Prestress losses are calculated for the mid-span section only. This is not a severe restriction, since most commonly, that is the only section where loss evaluation is needed. The gravity load moment \( M_g \) is automatically included during the first prestressing stages, whether pretensioned or post-tensioned. Therefore, the computer program will not analyze the member in Sections 2.4 and 2.5 correctly, since in that member the member weight moment is not activated until 3 days after tensioning of the first tendon. The beam can be analyzed approximately by combining the first and second stages. The estimated prestress loss would
be somewhat inaccurate for the initial time period immediately following the
tensioning of the first tendon. However, the error will diminish with time,
and will become negligible after a few weeks.

A more significant limitation of the computer program is that it per­
mits a total of only ten prestressing and/or loading stages. Exceeding this
limit will cause an error message and termination of calculations. If a
member with a more complicated fabrication and loading sequence is to be
analyzed, several stages must be combined in order not to exceed the ten
stage limit. The result would be approximate, however, inaccuracies will
only be significant near the times of the combined stages. At times several
years after the completion of the bridge structure, the error in estimated
prestress loss will again be negligible.

The computer program yields information on concrete and steel stresses,
and prestress losses in each steel element, at various times throughout the
entire service life of the structural member. In addition, it also returns
one "total percentage loss" of prestress force at a time specified by the
user. A mild restriction exists that this specified time must be later
than the last prestressing/loading stage.

Detailed descriptions of the input and output of the computer program
are given in the next several sections.

The computer program can be activated either independently or as a
 subroutine called from the PennDOT general prestressed concrete beam design
program. The description in Sections 3.2 and 3.4 pertains directly to the
independent usage of this program. For the use of this program as a sub­
routine, the user should consult the PennDOT fiscal and systems management
center for detailed instructions.
3.2 Input Instructions

The input for each beam analysis consists of a set of cards, each containing one to eight pieces of data. Each input data occupies one ten-column field on the 80-column card. All data are given in the FORTRAN F10.0 format, that is, each piece of data is entered in the usual digital form, including a decimal point. Any blank space in the 10-column field allotted to each input item is interpreted as zero.

Each set of input includes two mandatory cards in a beginning group, followed by combinations of four alternate groups. The composition of a complete data deck is as follows:

1. The beginning group
   One card no. 1, initiation of problem.
   One card no. 2, properties of the concrete and the beam cross section.

2. Pretensioning data
   One card no. 3 per stage of pretensioning.

3. Post-tensioning data
   Two cards no. 4 and 5, per stage of post-tensioning.

4. Deck slab data
   Two cards no. 6 and 7, information regarding the cast-in-place bridge deck.

5. Loading data
   One card no. 8 per stage of loading.

Obviously, only one beginning group (1) and one deck slab group (4) can be allowed. The other groups (2), (3) and (5) can be repeated as many times as necessary. All pretensioning naturally comes before any post-
tentioning or loading. The deck slab group (4) appears after all the post-tensioning but not necessarily all the loading stages. Group (5) cards deal with loading after deck slab casting only. Any loading occurring before the casting of deck slab is treated as post-tensioning (group 3) with zero additional prestressing force.

The detailed information contained on each card are as follows:

Card No. 1 (initiation)

<table>
<thead>
<tr>
<th>Columns</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>IPRE</td>
<td>Number of pretensioning stages</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Enter 0.0, if no pretensioning is involved.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For pretensioned and pre-post-tensioned members, this variable should usually be 1.0.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Value higher than 1.0 may be used if it is desired to distinguish among pretensioned strands in separate groups.</td>
</tr>
<tr>
<td>11-20</td>
<td>PLT</td>
<td>Concrete age for the desired &quot;total percentage loss&quot; of prestress force (days)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>This time must be later than the last prestressing/loading stage, and may not exceed the total &quot;life&quot; of the member, namely 36500 days.</td>
</tr>
</tbody>
</table>

Card No. 2 (properties of concrete member section)

<table>
<thead>
<tr>
<th>Columns</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>AGR</td>
<td>Net area of concrete section (in$^2$)</td>
</tr>
<tr>
<td>11-20</td>
<td>CMI</td>
<td>Moment of inertia of the net area of concrete (in$^4$)</td>
</tr>
<tr>
<td>21-30</td>
<td>YNET</td>
<td>Distance from the top of the beam to the centroid of the net concrete section (in)</td>
</tr>
<tr>
<td>31-40</td>
<td>SPANL</td>
<td>Span length (ft)</td>
</tr>
<tr>
<td>41-50</td>
<td>NSUCO</td>
<td>Code for concrete loss characteristics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0 Upper bound loss characteristics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0 Lower bound loss characteristics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.0 Average loss characteristics</td>
</tr>
</tbody>
</table>
The loss characteristics of concrete are dependent upon many factors including the mix composition and the properties of the aggregates. High strength concrete generally exhibits lower elastic and creep strains, and vice versa. In the absence of more definitive information on the concrete material, it is suggested that concretes with compression strength of 4000 psi or lower be deemed to have upper bound loss characteristics (1.0), and those with compressive strength of 5500 psi or higher be treated as having lower bound loss characteristics (2.0).

51-60 DEPTH The total depth of the beam (in.)

Card No. 3 (pretensioning data, one card for each pretensioning stage, I-th stage typical)

Note: The total number of No. 3 cards must agree with the value of IPRE.

<table>
<thead>
<tr>
<th>Columns</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>TIME(I)</td>
<td>Time of pretensioning (days)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number of days that pre-tensioning of steel precedes the end of curing prefixed with a negative sign.</td>
</tr>
<tr>
<td>11-20</td>
<td>NTYST</td>
<td>Code for strand size</td>
</tr>
<tr>
<td></td>
<td></td>
<td>This variable is used to define the cross-sectional area and the guaranteed ultimate tensile strength of each strand. Only 270-k 7-wire strands in used at the time of the initial research are included here as follows:</td>
</tr>
<tr>
<td>Code</td>
<td>Company</td>
<td>Diameter</td>
</tr>
<tr>
<td>------</td>
<td>--------------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>1.0</td>
<td>Bethlehem Steel Corporation</td>
<td>7/16 in.</td>
</tr>
<tr>
<td>2.0</td>
<td>C F &amp; I Corporation</td>
<td>7/16 in.</td>
</tr>
<tr>
<td>3.0</td>
<td>U.S. Steel Corporation</td>
<td>7/16 in.</td>
</tr>
<tr>
<td>4.0</td>
<td>Bethlehem Steel Corporation</td>
<td>1/2 in.</td>
</tr>
<tr>
<td>5.0</td>
<td>C F &amp; I Corporation</td>
<td>1/2 in.</td>
</tr>
<tr>
<td>6.0</td>
<td>U.S. Steel Corporation</td>
<td>1/2 in.</td>
</tr>
</tbody>
</table>

Low-relaxation strands:

<table>
<thead>
<tr>
<th>Code</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0</td>
<td>7/16 in.</td>
</tr>
<tr>
<td>8.0</td>
<td>1/2 in.</td>
</tr>
</tbody>
</table>

None of the companies listed above continues to produce prestressing strands at the present time. It is recommended that codes 1.0 and 6.0 be used for the stress-relieved strands of 7/16 in. and 1/2 in. diameter, respectively. These strands are closest to the values specified in the ASTM standards.

Code for steel relaxation characteristics

<table>
<thead>
<tr>
<th>Stress-relieved strands:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0  Bethlehem Steel Corporation</td>
</tr>
<tr>
<td>2.0  C F &amp; I Corporation</td>
</tr>
<tr>
<td>3.0  U.S. Steel Corporation</td>
</tr>
<tr>
<td>4.0  Bethlehem Steel Corporation</td>
</tr>
<tr>
<td>5.0  C F &amp; I Corporation</td>
</tr>
<tr>
<td>6.0  U.S. Steel Corporation</td>
</tr>
<tr>
<td>7.0  Average characteristics</td>
</tr>
<tr>
<td>8.0  Average characteristics</td>
</tr>
<tr>
<td>9.0  Average characteristics</td>
</tr>
</tbody>
</table>
Low-relaxation strands:
10.0  7/16 in. diameter
11.0  1/2 in. diameter
12.0  Average characteristics
13.0  A fictitious no relaxation steel

This variable is used to define coefficients used in the steel stress-strain-time relationship.

Relationships 1.0 through 6.0 refer to stress-relieved strands actually tested in the original research. In an earlier report (Fritz Laboratory Report No. 339.9) it was pointed out that the choice of steel characteristics causes only very small variations in the predicted loss behavior. Therefore, it is recommended that the average characteristics 9.0 should ordinarily be used. The designer may wish to use code 7.0 or 8.0 if the strand size is specified. Similarly, for low relaxation strands, code 12.0 is recommended unless the designer wishes to specify the strand size.

Code 13.0 refers to a fictitious no-relaxation steel, which was used in the development of the general procedure. It has no practical usage, and should never be employed.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>31-49</td>
<td>STRANDS</td>
</tr>
<tr>
<td>41-50</td>
<td>YDIST(I)</td>
</tr>
<tr>
<td>51-60</td>
<td>FSP(I)</td>
</tr>
</tbody>
</table>

Number of strands tensioned at this stage
Distance from top of beam to level of pretensioned steel at the midspan section (in.)
Initial tensioning stress (in fraction of the guaranteed ultimate tensile strength)
Card No. 4  (Post-tensioning data, one card for each post-tensioning stage, each to be followed immediately by a card No. 5)

<table>
<thead>
<tr>
<th>Columns</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>TIME(I)</td>
<td>Concrete age at post-tensioning (days after end of curing)</td>
</tr>
<tr>
<td>11-20</td>
<td>NTYST</td>
<td>Code for strand size</td>
</tr>
<tr>
<td></td>
<td></td>
<td>See description under Card No. 3. Where multi-strand tendon is used, this code refers to each individual strand</td>
</tr>
<tr>
<td>21-30</td>
<td>NSUST</td>
<td>Code for steel relaxation characteristics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>See description under Card No. 3</td>
</tr>
<tr>
<td>31-40</td>
<td>STRANDS</td>
<td>Number of strands tensioned at this stage. This refers to the total number of 7-wire strands within the tendons.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Enter 0.0 if the event at this stage is loading only. In this case the only other data needed on Cards 4 and 5 are TIME(I) and CMBM. All other entries may have any legitimate value.</td>
</tr>
<tr>
<td>41-50</td>
<td>YDIST(I)</td>
<td>Distance from top of beam to level of steel being tensioned, at midspan (in.)</td>
</tr>
<tr>
<td>51-60</td>
<td>FSP(I)</td>
<td>Initial jacking stress (in fraction of guaranteed ultimate tensile strength).</td>
</tr>
</tbody>
</table>

Card No. 5  (Post-tensioning data, one card for each post-tensioning stage, immediately following card no. 4).

<table>
<thead>
<tr>
<th>Columns</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>Y</td>
<td>Code for jacking process</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.0 if jacked from one end only.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.0 if jacked from both ends simultaneously.</td>
</tr>
<tr>
<td>11-20</td>
<td>XKK</td>
<td>Wobble coefficient (ft.(^{-1}))</td>
</tr>
<tr>
<td>21-30</td>
<td>DELT</td>
<td>Anchorage seating distance (in.)</td>
</tr>
<tr>
<td>31-40</td>
<td>XMU</td>
<td>Coefficient of friction</td>
</tr>
<tr>
<td>41-50</td>
<td>EE</td>
<td>Distance from top of beam to level of steel being tensioned, at end of beam (in.)</td>
</tr>
<tr>
<td>51-60</td>
<td>CMBM</td>
<td>Additional permanent moment applied to the midspan section at this time (k-in.)</td>
</tr>
<tr>
<td>61-70</td>
<td>ALENGTH</td>
<td>New span length of member (ft.). This variable is used in segmental structure to define the gradual change of member length. If there is no change in member length, these columns should be left blank.</td>
</tr>
</tbody>
</table>
Card No. 6 (A blank card, placed after the last set of post-tensioning data, to be followed immediately by card no. 7).

Card No. 7 (Deck information, immediately following card no. 6)

<table>
<thead>
<tr>
<th>Columns</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>STIME</td>
<td>Concrete age when deck slab is cast (days after the end of curing)</td>
</tr>
<tr>
<td>11-20</td>
<td>FCSL</td>
<td>Compressive strength of deck concrete (psi)</td>
</tr>
<tr>
<td>21-30</td>
<td>FCBM</td>
<td>Compressive strength of beam concrete (psi)</td>
</tr>
<tr>
<td>31-40</td>
<td>CMBM</td>
<td>Additional permanent bending moment (other than the weight of deck slab) applied at this time and resisted by the precast beam along (k-in.)</td>
</tr>
<tr>
<td>41-50</td>
<td>TSL</td>
<td>Structural thickness of deck slab (in.)</td>
</tr>
<tr>
<td>51-60</td>
<td>TSLW</td>
<td>Total thickness of deck slab, including the allowance for wearing surface (in.)</td>
</tr>
<tr>
<td>61-70</td>
<td>WSL</td>
<td>Width of deck slab attributed to each beam (in.)</td>
</tr>
<tr>
<td>71-80</td>
<td>CMCO</td>
<td>Additional permanent bending moment applied at this time and resisted by the composite section (k-in.)</td>
</tr>
</tbody>
</table>

Card No. 8 (loading information, one card for each loading stage)

<table>
<thead>
<tr>
<th>Columns</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>STIME</td>
<td>Concrete age when loading takes place (days after the end of curing)</td>
</tr>
<tr>
<td>11-20</td>
<td>CMCO</td>
<td>Additional permanent bending moment applied at this time (k-in.)</td>
</tr>
</tbody>
</table>

3.3 Examples of Input Data

The input data sets for the illustrative examples described in Chapter II are listed below for demonstrative purposes:

Example 1, Pretensioned Member

Card 1: 1.0, 36500
Card 2: 599.0, 213078.0, 29.03, 70.0, 1.0, 54.0
Card 3: -2.0, 5.0, 8.0, 16.0, 51.23, 0.70
Card 6: Blank
Card 7: 180.0, 4000.0, 5000.0, 0.0, 8.0, 8.0, 87.0, 0.0
Card 8: 240.0, 996.0

Example 2, Post-tensioned Member
Card 1: 0.0, 36500
Card 2: 862.0, 298260.0, 22.19, 96.0, 1.0, 52.0
Card 4: 7.0, 8.0, 12.0, 10.0, 49.0, 0.70
Card 5: 1.0, 0.0002, 0.25, 0.25, 20.0, 0.0,
Card 4: 40.0, 8.0, 12.0, 12.0, 49.25, 0.70
Card 5: 1.0, 0.0002, 0.25, 0.25, 46.0, 0.0,
Card 4: 42.0, 8.0, 12.0, 10.0, 45.0, 0.70,
Card 5: 1.0, 0.0002, 0.25, 0.25, 8.0, 0.0,
Card 8: 90.0, 3828.0

There are three sets of post-tensioning data, but no deck slab.

Example 4, Pre-post-tensioned Member
Card 1: 2.0, 7300
Card 2: 1046, 470081.0, 32.025, 103.1, 2.0, 63.0
Card 3: -1.0, 1.0, 9.0, 6.0, 3.0, 0.70
Card 3: -1.0, 1.0, 9.0, 40.0, 55.3, 0.70
Card 4: 90.0, 1.0, 9.0, 12.0, 50.5, 0.67
Card 5: 1.0, 0.0002, 0.1875, 0.25, 11.5, 0.0,
Card 4: 90.0, 1.0, 9.0, 12.0, 54.75, 0.656
Card 5: 1.0, 0.0002, 0.1875, 0.25, 23.5, 0.0,
Card 4: 90.0, 1.0, 9.0, 12.0, 59.0, 0.637
Card 5: 1.0, 0.0002, 0.1875, 0.25, 35.5, 0.0,
Card 6: Blank
Card 7: 120.0, 3500.0, 5750.0, 0.0, 7.5, 8.0, 84.0, 3348.0

There are two sets of data for pretensioning, and three sets for post-tensioning, one set for deck slab, but no
separate loading stage.

3.4 **Output Description**

The computer program provides a complete description of steel and concrete stress distribution in the structural member throughout its assumed service life. Stress and prestress evaluations are made before and after each prestressing and/or loading stage (except that when two stages occur in immediate succession, only one intermediate evaluation is made), at the specified time for percentage prestress loss (PLT), and at a series of preselected concrete ages covering the total time range. Besides the description of stress distribution in the member and the prestress in each steel element, the output at each evaluation also includes the total prestress force and the total steel force, the location of the total forces, as well as the percentage loss of total prestress force. At each prestressing stage, the input information is listed in the output with complete annotation. In addition, the incremented value of "total initial prestress force" is listed in the output. This value will be used as the bases for "percentage prestress loss" calculations for subsequent times until the next prestressing stage, when the total initial prestress force will be increased again. Annotated event information is also outputted after each loading stage and the deck slab casting event. The percentage loss of total initial prestress force at the special specified time PLT is stored under the name PLOSS. Both PLT and PLOSS remain available at the end of the computer run, and can be made available to subsequent use in a larger computer program calling FOUR02 as a subroutine. Also available is a variable named FINIT, which represents the sum of all initial prestressing forces.

Appendix C shows the images of the input cards as well as the computer output for example 4.
IV. REFERENCES


6. Huang, Ti On Stress Estimation of a Prestressed Concrete Member, Journal of the Prestressed Concrete Institute, Vol. 17, No. 1, Jan-Feb 1972.


V. ACKNOWLEDGMENTS

This report was prepared under an Implementation agreement with the Pennsylvania Department of Transportation in conjunction with the United States Federal Highway Administration. These same agencies, together with the Reinforced Concrete Research Council, also sponsored the previous research effort. The interest and support of these organizations are gratefully acknowledged.

The research work leading to the proposed procedures described in this report was conducted at the Fritz Engineering Laboratory of Lehigh University. Dr. Lynn S. Beedle is the director of the laboratory.

The author is grateful to Mr. Ronald Arner, District 3 Bridge Engineer, and Mr. Robert L. Jones, District 5 Bridge Engineer, for their help in the development of the example problems used in this report.

Many individuals made valuable contributions in the course of the extended research effort. The author wishes to recognize particularly his former assistants, E. G. Schultchen, A. Rokhsar, D. C. Frederickson, R. J. Batal, H. T. Ying, J. Tansu, C. S. Hsieh, P. Rimbos and B. Hoffman.

The manuscript of this report was typed by Mrs. J. Frey and Ms. L. I. Wunder. The graphs were prepared by Mr. J. Gera and Ms. S. Balogh.
1.6.2 Notations and Definitions

(A) Notations

Listed below are new notations to be added. In conjunction, the following existing notations should be deleted: $CR_c$, $CR_s$, $CR_{sp}$, $f_{cd}$, $f_{cf}$, $\Delta f_s$, $L$, $SH$, $T$, $T_0$, $T_x$, $E_c$, $f_{cir}$, $f_{cds}$ and FR. Unless specifically indicated otherwise, all quantities are expressed in consistent kip-inch-day units. All stresses are positive in tension.

- $a_{si}$ = Area of the prestressing element tensioned at the $i$-th stage
- $A$ = Area of member cross section
- ACF = Prestress loss due to friction and anchorage seating
- $C_s$ = Coefficient for estimation of shrinkage correction, see Eq. 7
- CR = Prestress loss due to creep of concrete
- CRA = Correction to prestress loss for multistage post-tensioning
- e = Eccentricity of prestress
- $E_s$ = Modulus of elasticity of prestressing steel
- $f_c$ = Fiber stress in concrete
- $f_{cgi}$ = Concrete fiber stress, at level of steel, caused by member's own weight activated at the time of $i$-th stage $t_{ai}$
- $f_{cli}$ = Concrete fiber stress, at level of steel, caused by permanent loads (including members weight), activated at the $i$-th stage
- $f_{cp}$ = Prestress in concrete
- $f_p$ = Prestress in steel

*Notations preceded by an asterisk are used in Commentary only.
\( f_{pj} \) = Initial tensioning stress in steel
\( f'_s \) = Specified ultimate tensile strength of prestressing steel
\(*f_s\) = Stress in prestressing steel
\( f_{sd} \) = Increment of concrete stress, at level of steel, due to the prestressing of the i-th stage

\( GL \) = Component of prestress loss, used for post-tensioned steel only, for the effect of member's own weight

\( IL \) = Initial prestress loss, immediately after introduction of concrete prestress
\( k \) = Combined friction and curvature coefficient = \( K + \mu \phi \), in \( ft^{-1} \)
\( l_a \) = Anchorage length, in feet

\( LD \) = Effect of applied permanent load on final prestress loss
\(*M\) = Bending moment on section caused by applied load, see Fig. C.1
\( M_{gi} \) = Moment caused by member's own weight, activated at the i-th stage
\( M_i \) = Bending moment activated at the i-th stage (\( M_i \) includes \( M_{gi} \))
\( n \) = Modular ratio of steel to concrete
\(*P\) = Axial compressive force on section caused by applied load, see Fig. C1

\( PL \) = Prestress loss at concrete age of \( t \)
\( REL_{1} \) = Relaxation loss in pretensioned strands occurring before transfer
\( S \) = Correction to prestress loss, accounting for the shrinkage occurring before post-tensioning

\( SRL \) = One part of the final prestress loss, independent of concrete stress
\( t \) = Age of concrete, starting from end of curing
\( t_{si} \) = Age of concrete when the i-th stage event takes place (for pretensioned steel, \( t_{si} \) is negative for Fig. 1 but taken as zero elsewhere)
TL = Final prestress loss at end of service life
x = Distance of a given section from the jacking end, in ft
xa = Distance of a given section from the end of the anchorage length, in ft.
*y = Distance of elementary area from the centroid axis of cross section, see Fig. C.1
Δa = Anchorage seating distance, in feet
φ = Curvature of tendon profile, in radians per foot.

The last subscript in ai, fci, fsci, Mgi, Mi and tsi stands for the specific individual stage or element, and may take on any numerical or symbolic value. E.g., a sk refers to the area of k-th element, t sm refers to the time of m-th stage, M 2 refers to the moment at stage 2, etc.

(B) Definitions

(1) Prestressing Element: A prestressing element designates a group of prestressing steel which are tensioned, and induce prestress in the concrete, at a common time. An element may refer to one or more post-tensioned tendons, or the entire collection of pretensioned strands.

(2) Stage: A stage is a specific time in the life history of a prestressed concrete member, when a permanent change of loading or prestressing takes place. The event occurring may be the introduction of additional prestress, the activation of additional permanent load, or both.

(3) Prestress: Prestress refers to the material stress which is not directly caused by the external loads. In practice, it is evaluated as the difference between the actual material stress
and the direct elastic stress caused of the external loads, which include the weight of the members itself.

(4) Initial Prestress: The initial prestress of a prestressing element refers to its stress at the jacking end immediately before the anchoring and releasing of the tensioning device.

(5) Loss of Prestress: Loss of prestress refers to steel only, and is measured with reference to the initial prestress. At any given time, the prestress loss in a prestressing element is the difference between its current prestress and its initial prestress.

1.6.7 Loss of Prestress

(A) General

Loss of prestress is calculated for each element and each time interval separately. The loss in the \( k \)th element \( a_{sk} \) at time \( t \), within the time interval between the \( m \)th and the \( (m+1) \)th stages, \( (m > k) \), is calculated by the following equation.

\[
PL = IL + 0.22(TL-IL) \log(t-t_{sk})
\]

where \( t_{sk} \) is taken as zero for pretensioned tendons. However, \( PL \) shall not be taken as less than the value calculated for time \( t_{sm} \) from the preceding time interval. The quantities IL and TL are calculated according to (B), (C) and (D) of this article.

(B) Initial Loss IL, Corresponding to the Initial Time \( t_{sk} \)

\[
IL = REL + ES + ACF + GL
\]
where REL₁ = initial relaxation loss in pretensioned strands occurring before transfer, from Fig. 1. This term is omitted for post-tensioned tendons.

ES = Elastic shortening loss

\[ ES = -n \sum_{i=k+1}^{m} f_{sdi} \quad \text{for post-tensioned elements} \]

\[ = -n \sum_{i=k}^{m} f_{sdi} \quad \text{for pre-tensioned elements} \]

\[ f_{sdi} = -a_{si} f_{pj} \left( \frac{1}{A} + \frac{e_{i} e_{k}}{I} \right) \]

ACF = Loss due to friction and anchorage seating, see Article 1.6.7(C)

GL = Loss in post-tensioned elements due to member weight

\[ GL = n \sum_{i=1}^{k} f_{cgi}. \quad \text{This term is omitted for pretensioned elements.} \]

\[ f_{cgi} = \frac{e_{k}}{g_{i} I} \]

(C) Friction and Anchorage Seating Loss, ACF

The loss of prestress due to friction and anchorage seating shall be calculated by the basic equation

\[ ACF = f_{pj} [1 - e^{-(Kx+\mu)}] \quad (3) \]

where \( K, \mu \) = Wobble and curvature friction coefficient, respectively

\( x \) = Distance from the jacking end, but see below

\( \alpha \) = Total angle change in distance \( x \), including those in vertical as well as horizontal planes.
The anchorage seating loss is nonuniformly distributed within a length \( l_a \). To include this loss component in Eq. 3, the distance \( x \) shall be taken as \( l_a + x_a \), where \( x_a \) is the distance from the end of the anchorage length \( l_a \) to the section in question. The anchorage length \( l_a \) is controlled by the seating slippage distance \( \Delta_a \). For the case where the tendon profile has uniform curvature within the distance \( l_a \), this length is determined as follows:

\[
 l_a = -\frac{1}{k} \ln \left( 1 - \sqrt{\frac{E_s \Delta}{f_p j}} \right) \quad (4)
\]

where \( k = K + \mu \frac{\Delta}{x} \).

If the friction coefficients are small, the tendon profile is flat and the seating slippage distance is small (\( kx \leq 0.30 \)), simpler equations may be used for \( ACF \) and \( l_a \):

\[
 ACF = f_p j (Kx + \mu \Delta) \quad (5)
\]

\[
 l_a = \sqrt{\frac{E_s \Delta}{f_p j} / k} \quad (6)
\]

\( K \) and \( \mu \) values shall be determined experimentally for the materials used. When experimental data are not available, the values in the following table may be used.

<table>
<thead>
<tr>
<th>Type of Steel</th>
<th>Type of Duct</th>
<th>( (K/\text{ft}) )</th>
<th>( \mu )</th>
<th>( (K/\text{m}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire or galvanized strand</td>
<td>Bright Metal Sheathing</td>
<td>0.0020</td>
<td>0.30</td>
<td>0.0066</td>
</tr>
<tr>
<td></td>
<td>Galvanized Metal Sheathing</td>
<td>0.0015</td>
<td>0.25</td>
<td>0.0049</td>
</tr>
<tr>
<td></td>
<td>Greased or asphalt-coated and wrapped</td>
<td>0.0020</td>
<td>0.30</td>
<td>0.0066</td>
</tr>
<tr>
<td></td>
<td>Galvanized rigid</td>
<td>0.0002</td>
<td>0.25</td>
<td>0.0007</td>
</tr>
<tr>
<td>High-strength bars</td>
<td>Bright Metal Sheathing</td>
<td>0.0003</td>
<td>0.20</td>
<td>0.0010</td>
</tr>
<tr>
<td></td>
<td>Galvanized Metal Sheathing</td>
<td>0.0002</td>
<td>0.15</td>
<td>0.0007</td>
</tr>
</tbody>
</table>
(D) Final Total Loss, TL, for End of Service Life at \( t = 36500 \) Days

\[
TL = IL + SRL - REL - S + CR - CRA - LD
\]  

(7)

where SRL = Component of loss independent of concrete stress, from Fig. 2.

\[ S = \text{Correction for shrinkage occurring prior to } t_{sk}, \text{ for post-tensioned tendons only.} \]

\[ = C_s \log t_{sk} \]

\[ C_s = 4.0 \text{ and } 2.2, \text{ respectively, for upper bound and lower bound loss estimates.} \]

\[ CR = \text{Loss due to creep } = -1.2 n \Sigma_{i=1}^{m} f_{sd_i}. \]

\[ CRA = \text{Correction for creep strain occurring prior to } t_{sk} \]

\[ = -n \Sigma_{i=1}^{k-1} (0.26 f_{sd_i} + 0.44 f_{c_{li}}) \log(t_{sk} - t_{si} + 1) \]

\[ LD = \text{Long term effect of applied loads} \]

\[ = 2n \Sigma_{i=1}^{m} f_{c_{li}} \]

\[ f_{c_{li}} = \text{Concrete stress caused by permanent load, including member weight, activated at stage } i \]

\[ = \frac{e_k}{M_i I} \]
Fig. 1 Initial Relaxation Loss in Pretensioned Strands

Transfer Time (t=fsi) days (log scale)

Low Relaxation Strands

f_{pj} = 0.8fs_i

Stress Relieved Strands

REL, % fs_i
Fig. 2 SRL Part of Final Prestress Loss
II. COMMENTARY

The proposed procedure is a simplified version of a general procedure which is more suitable for computer operations. This simpler version is designed to facilitate manual applications.

The general procedure makes use of stress-strain-time characteristic relationships of the concrete and steel materials. Linking these relationships with the compatibility and equilibrium conditions enables a complete analysis of the prestressed concrete member at any time during its service life. The procedure is completely rational, the determination of stresses is direct, and the interaction of the long-term behavior of the two materials is automatically taken care of. On account of the rational approach, extension for new material or new construction procedure can be done easily. Only the material characteristic relationship needs to be determined experimentally. Details of the general procedures are given in several published reports (Fritz Laboratory Report 339.9, 382.5, 402.4). A brief summary is contained in part V of this document.

The simpler procedure proposed here for specification implementation was developed based on a parametric study using the general procedure. Like the general procedure, it is applicable to prestressed concrete members of all types, including those with multi-stage prestressing.

The following specific commentary is keyed to the sections and subsections of the proposed specifications, part II.

1.6.2(B) (2) Stage: The individual stages are identified by the age of concrete when the event takes place. Pretensioned strands are stretched before the casting of concrete, but do not induce concrete prestress until
transfer at the end of curing (t = 0). Therefore, the associated
time \( t_{sl} \) is negative for the evaluation of REL\(_1\) in Fig. 1, but taken
as zero for all other purposes.

In this document, quantities related to a certain stage are designated
by a subscript signifying the sequential order of the stage. Thus,
the \( i \)-th stage takes place at time \( t_{si} \), when prestress is induced by
element \( a_{si} \), and simultaneously an increment of permanent load is
activated, causing bending moment \( M_i \) (which may include a part \( M_{g1} \)
due to member weight). Either \( a_{si} \) or \( M_i \) may be zero.

(3) Prestress: The definition of prestress recognizes its load-independent
and self-equilibrated characteristics. It is directly derivable from
the familiar equations for fiber stresses in a prestressed member.
These equations show the material stress as the sum of the prestress
and the direct effect of the applied loads.

\[
f_s = f_p + n\left(-\frac{P}{A} + \frac{M_e}{I}\right)
\]

\[
f_c = f_{cp} + (-\frac{P}{A} + \frac{M_y}{I})
\]

where \( A, I, e \) and \( y \) refer to the transformed cross section of the member,
in which the steel is replaced by \( n \) times its area in concrete. The
sign convention for the load effects and distances are given in Fig.
C.1. These equations imply that the prestresses are a fixed character-
istic of the section in question, and are not influenced by the present
loading condition. On the other hand, prestresses are time dependent,
and the creep and relaxation behaviors are both controlled by the total
stress history. Consequently, any sustaining (permanently applied)
load would have an indirect effect on the prestresses. The weight of the member is a load exerted by an external agent (i.e., the earth), therefore, it has no direct effect on the prestress, and must be included in the load effects to be removed in the evaluation of prestress.

Under the zero load condition, only prestresses are present in a prestressed member, and they must satisfy the static equilibrium. Therefore, corresponding to the $i$-th stage prestressing:

$$ f_{cp} = - \frac{a_{si} f_{p}}{A} + \frac{a_{si} f_{p} e_i y}{I} $$

where $A$, $I$, $e$ and $y$ refer to the cross section effective in resisting the tensioning of prestressing element $a_{si}$. For pre-tensioned members, this would be the transformed section at the transfer time, although ordinarily the gross section properties can be used without inducing serious errors. (Exceptional cases would be where the section is heavily prestressed and the modular ratio is high, a detailed discussion is given in project report 339.9.) For post-tensioned members, the effective section includes the concrete and all previously anchored steel, and changes from stage to stage. Any empty space occupied by the ducts should be deducted.

On account of the varying effects of external loads along the length of a member, the prestress in a given element also varies along the length. Therefore, to be strictly meaningful, prestress values must be identified not only with the time, but also with the location.
(4) Initial prestress: The initial prestress is the last amount subjected to direct control. After anchorage and release, stresses and pre-stresses change as dictated by the material and loading characteristics but are no longer directly controllable.

For pre-tensioned strands, the friction and anchorage seating losses are very small, and the initial prestress may be taken as the stress in the strands after anchoring to the prestressing bed.

(5) Prestress loss: The principal sources of prestress loss include friction and anchorage seating, elastic deformation, creep, shrinkage, and relaxation. While the first two components can be accurately predicted on the basis of rational theories, the understanding of the last three components is not complete. Furthermore, these three time-dependent effects are strongly interdependent such that it is not appropriate to separately estimate each effect and then sum them together. The proposed procedure takes full account of the inter-relation among the several components.

1.6.7(A) General

Prestress loss differs for each prestressing element, and for different locations along the length of the member. For the purpose of design, evaluation of losses is usually needed only at the section of maximum service load moment. For a simply supported member, this section may be taken at the midspan.

From a computerized parametric study, it was found that without introducing additional prestress or permanent load, the growth of prestress
loss with time can be closely approximated by the linear semi-logarithmic relationship represented by Eq. 1. This equation shows that the prestress loss is IL at the initial time $t_{sk}$ and TL at the end of service life, taken to be 100 years after the termination of curing ($t = 36500$ days).

It is emphasized that the linear relationship is valid only within each time interval between two consecutive stages. At the end of an interval, the addition of prestress (tensioning of new tendons), or permanent load (caused by members weight or other additional dead load), or both, causes increment of stresses in concrete. These stress increments, $f_{adi}$, $f_{c_{gi}}$ and $f_{c_{gi}}$, change IL and TL for all previously anchored steel elements, resulting in changed line segments for the new time interval, as shown in Fig. C.2.

If the stage event involves only the addition of a permanent load (e.g. casting of deck slab), there will be no change in IL, but a decrease in TL, resulting in an abrupt decrease of prestress loss at the stage time. This is caused by certain approximations used in this simplified procedure. The real behavior, as obtained by the basic general procedure, is more gradual, but distinctly nonlinear (Fritz Laboratory Report 382.5). For the sake of simplicity, such sudden decrease is ignored, and the prestress loss is taken as remaining constant for a part of the next time interval. Fig. C.2 shows the typical variation of prestress loss over several time intervals.
1.6.7(B) **Initial Loss**

IL is the loss of prestress calculated for the time of tensioning \((t = t_{sk})\), and represents the difference between the jacking stress \((f_{pj})\) and the prestress at the desired location immediately after anchorage. For pretensioned elements, it is calculated for \(t_{sl} = 0\).

REL applies to pretensioned strands only, it accounts for the relaxation loss in the strands before transfer. For its determination from Fig. 1, the actual negative values for \(t_{sl}\) prestressing is used.

ES represents the effect of elastic deformation caused by successive prestressing. The lower limit of summation is different for pre- and post-tensioned elements. In pretensioned strands, the shortening of concrete upon transfer causes a corresponding loss in the strands. In contrast, the post-tensioned tendons are tensioned against the concrete members, the jacking stress being measured after concrete has already shortened. Consequently, post-tensioned tendons do not cause an EL loss in themselves.

GL represents a nominal loss of prestress in post-tensioned tendons, on account of the dead load at the time of tensioning. The cambering of the member upon post-tensioning causes the \(f_{cg1}\) stress to develop at the time when \(f_{pj}\) is being measured. In line with the definition of prestress given in section 2.3, this effect must be removed to arrive at the prestress. This term is not used for pretensioned strands, since the tensioning of pretensioned strands does not coincide with the cambering of the member.

For a simple pretensioned member, IL is evaluated at \(t = 0\), ACF and GL are omitted, and
\[ IL = REL_1 + ES \]

\[ ES = n A_{ps} \frac{f}{pj} \left( \frac{1}{A} + \frac{e^2}{I} \right) \]

where \( A_{ps} \) = Total area of pretensioning strands.

1.6.7(C) Anchorage and Friction Losses

These losses are caused by the friction between the prestressing tendons (or strands) and the conduit along which its slides during the tensioning or releasing process. The combined amount of these losses is controlled by the surface roughness, the curvature of the tendon profile, and the seating slippage distance, and is dependent on the distance from the jacking end. The basic equation (3) is derived from the principles of statics.

It is important to note that \( \alpha \) represents the sum of all changes in directions, within the distance \( x \), in all longitudinal planes (vertical, horizontal as well as inclined). Resolving an angle change in an inclined plane into its horizontal and vertical components for summation into \( \alpha \) results in a conservative but reasonable approximation, slightly over-estimating the loss.

For pretensioned strands, friction exists only at the bulkheads and deflecting devices and can be relieved before placing concrete. Also, the seating distance is insignificant in comparison with the length of the prestressing bed. Consequently, the component ACF can be, and usually is, neglected.
Because of friction, the anchorage seating loss in a post-tensioned tendon is severely nonuniform in its distribution, being concentrated near the jacking end. As distance from the jacking end increases, the anchorage seating loss decreases rapidly, while the frictional loss increases at a slower rate, resulting in a gradual decrease of ACF. Beyond a certain distance \( l_a \), the anchorage seating loss disappears, and the ACF reflects only the gradually increasing friction effect. When using Equation 3 to calculate ACF at a location within the anchorage length, the distance \( x \) should be taken as \((l_a + x_a)\), where \( x_a \) is the distance from the end of the anchorage length \( l_a \), as shown in Fig. C.3.

The method for evaluating the anchorage length \( l_a \), and the derivation of equations for several typical conditions have been presented in several reports and publications (Report 402.3 and publication 1). Equations 4 and 6 are for the cases where the tendon profile has uniform curvature over the length \( l_a \) (e.g. a flat parabolic profile). In this case, the angle change \( \alpha \) is directly proportional to the distance \( x \), and a combined friction coefficient can be formulated

\[
k = K + \mu \phi
\]

where \( \phi = \text{Curvature of the tendon profile, in radians per foot.} \) Equation 4 is derived by equating the shortening of the tendon within the anchorage length to the seating slipping distance \( \Delta_a \). At \( x = l_a \) (or \( x_a = 0 \)), the ACF is smallest,

\[
(\text{ACF})_{\text{min}} = \frac{\sqrt{E \Delta_a k f}}{s a pj}
\]
If the friction effect is small \((kx < 0.30)\), the exponential function in Eq. 3 can be approximated by a linear expansion, resulting in Eq. 5. Equation 4 is similarly simplified into Eq. 6. The equation for \((ACF)_{\min}\) remains unchanged for this case.

1.6.7(D) Final Loss

The final prestress loss is calculated for the end of the assumed service life of the member. It includes the long-term effects of shrinkage creep and relaxation.

\(SRL\) is a quantity independent of the stresses in concrete. It is rather dependent upon the shrinkage and relaxation characteristics of the materials. Its evaluation is empirically obtained from Fig. 2.

\(S\) is a correction term for \(SRL\), reflecting the shrinkage taking place prior to time \(t_{sk}\). That portion of the shrinkage strain will have no effect on the losses in the element \(a_{sk}\).

\(CR\) represents essentially the prestress loss due to creep. The negative sign in the defining formula is needed because \(f_{sd1}\) stresses are generally negative (compression). \(CRA\) is a correction term for the creep strain taking place prior to the tensioning of the \(k\)-th element. Similar to the \(S\) correction, these creep strains also have no effect on the loss in the element \(a_{sk}\).

\(LD\) represents the long-term effect of the sustaining external loads. Transient loads are not included in the calculation. These loads appear in short periods of time only, and their effects on prestress losses can be safely ignored.
For a simple pretensioned member, S and CRA are zero, and Equation 6 is simplified

$$ TL = SRL + EL + CR - LD $$

Once again, it is emphasized that IL and TL change for each time interval. However, most of the terms in Equations 2 and 6 remain unchanged. It is only necessary to calculate the changes in EL, CR and LD which are controlled by the two stress increments $f_{\text{sd}i}$ and $f_{\text{cd}i}$ (or $f_{\text{cg}i}$).
Fig. C1 Sign Convention for Applied Loads and Distances
Fig. C2 Typical Variation of Prestress Loss with Time

- Loss Taken as Constant
- Temporary Decrease Neglected
- Increase Due to Prestress

**Fig. C2 Typical Variation of Prestress Loss with Time**
Fig. C3 Friction and Anchorage Seating Losses
APPENDIX B

Flow Diagram for Computer Program
FOUR02

Input Number of Pretensioning Stages (Card 1)

Input Section Properties (Card 2)

Initialize Parameters
Subroutine INITI

Set Stage Counter

Analyze for Pretensioning
Subroutine PRE

Input Next Event
(Card 4, 6, 8 or EOF)

EOF
No more stages

Card 6
Add deck slab
Subroutine LASTS

Card 8
Add external moment
Subroutine ADDM

Card 4
Analyze for intermediate time Subroutine INTERM

Post-tensioning Subroutine POST

End

Analyze for Remaining Life to 100 years
Subroutines PREDI, PROUT

A

A
Subroutine ADIM

Analyze for Times up to $t_{si}$ before Loading Subroutines PREDI, PROUT

Calculate Equivalent Load System

$a_{si} = 0$

Calculate Stress Increments Subroutine PREDI

Output Conditions after Loading Subroutine PROUT

Return
Subroutine ANCFR

Calculate Anchorage Length

Compare Anchorage Length with Effective Length, also Compare Location of Critical Sections

Calculate Steel Stress at Critical Section after Anchorage and Friction Losses

Return
Subroutine

CONCS

\[ Q_1 = D_1 + D_2 \log(t_c + 1) \]
\[ Q_2 = 0 \]

If \( t_c > t_{s1} + 1 \)
Add Creep Terms to \( Q_1, Q_2 \)

If \( t_c > t_{s2} \)
Add \( f_{sdi} \) terms to \( Q_1 \)

Return
Subroutine INITI

Define the Concrete Characteristic Coefficients

Calculate Moment Due to Member's Own Weight

Set Initial Values for Control Variables

Return
Subroutine

INTERM

Analyze Section for Specified Time
Subroutine PREDI

Output Results
Subroutine PROUT

Return
Subroutine \textit{LASTS}

- Input Data on Deck Slab (Card 7)
- Analyze for Times before Deck Casting (Subroutines \textit{PREDI}, \textit{PROUT})
- Calculate Loading Due to Deck Estimate $h_1$, $h_2$
- Repeat 5 times
  - Analyze after Deck Casting Subroutine \textit{PREDI}
  - Revise $h_1$, $h_2$
- Calculate Stresses after Deck Casting
- Output Results Subroutine \textit{PROUT}
- Return
Subroutine POST

Input Additional Data (Read Card 5)

Adjust Member Weight Moment if Needed

Analyze before Post-Tensioning Subroutines PREDI, PROUT

Calculate Post-Tensioning Force Subroutine ANCFR

Calculate Equivalent Load System Estimate $h_{14}$, $h_{24}$

Repeat 5 Times

Analyze after Post-Tensioning Subroutine PREDI

Revise $h_{14}$, $h_{24}$

Calculate $k_{41}$

Calculate Steel Stresses and Prestresses after Post-Tensioning

Output Results Subroutine PROUT

Return
Subroutine

PRE

Input Pretensioning Data (Card 3)
Increment Stage Center
Calculate Initial Steel Stresses and Strains

Calculate Steel Stresses before Transfer

Analyze for Conditions after Transfer
Subroutines PREDI, PROUT

Return
Subroutine PREDI

1. Initialize Values for U and V Coefficients

2. For Each Stage of Prestressing Steel, $a_{si}$
   - Select $P_1$, $P_2$, and $P_3$ for $a_{si}$
   - Get $Q_1$ and $Q_2$ for the Location of $a_{si}$ (Subroutine CONCS)
   - Calculate $R_{1i}$, $R_{2i}$, $R_{3i}$
   - Increment U and V Coefficients

3. Solve Simultaneous Equations for $g_1$ and $g_2$

Return
Subroutine PROUT

Output Concrete Stress at the Top of the Beam

Output Concrete Stress, Steel Stress, and Steel Prestress for Steel Elements of Each Stage

Output Concrete Stress at the Bottom of the Beam

Calculate and Output the Total Steel Force and its Eccentricity

Return
APPENDIX C

Sample Computer Input and Output

As an illustrative example for the usage of the computer program, the images of the input data deck for example problem 4, the pre-post-tensioned member, are reproduced on the next page. (Refer to Section 3.2, p. 44 for input format). The complete computer output is reproduced starting from page 91. (For comparison with the manual solution, please refer to Section 2.6, p. 30.)
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DISTANCE FROM TOP OF BEAM TO CENTROID OF THE NET SECTION (IN) = 32.03
TYPE OF CONCRETE SURFACE = LOW BOUND
TOTAL DEPTH OF BEAM = 63.00
SPAN LENGTH = 103.10
FS = 188.6957
TIME OF TENSIONING = -1.00 DAYS
TYPE OF STEEL SURFACE : ALL BOTH
TYPE OF PRESTRESSING STRANDS = BET 7/16
NUMBER OF STRANDS = 6.0
TENSIONED TO .700 OF MAXIMUM

FS = 188.6957
TIME OF TENSIONING = -1.00 DAYS
TYPE OF STEEL SURFACE : ALL BOTH
TYPE OF PRESTRESSING STRANDS = BET 7/16
NUMBER OF STRANDS = 40.0
TENSIONED TO .700 OF MAXIMUM

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CONDITIONS AT TIME=0.0 DAYS, AFTER THE TENDONS HAVE BEEN RELEASED
TOTAL INITIAL PRESTRESS FORCE = 998.20 KIPS
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ECCENTRICITY OF PRESTRESS = 48.16
TOTAL LOSS OF PRESTRESS FORCE = 6.91 PERCENT
TOTAL STEEL FORCE = 946.17 KIPS
ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 48.51 IN

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TOTAL PRESTRESS FORCE = 928.60

CONDITIONS AT TIME = 0.1 DAYS

ECCENTRICITY OF PRESTRESS = 48.16
TOTAL LOSS OF PRESTRESS FORCE = 6.97 PERCENT
TOTAL STEEL FORCE = 945.55 KIPS
ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 48.51 IN

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TOTAL PRESTRESS FORCE = 919.56

CONDITIONS AT TIME = 2.0 DAYS

ECCENTRICITY OF PRESTRESS = 48.16
TOTAL LOSS OF PRESTRESS FORCE = 7.88 PERCENT
TOTAL STEEL FORCE = 936.52 KIPS
ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 48.52 IN
## Conditions at Time = 3.0 Days

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Total Prestress Force: 913.42
Eccentricity of Prestress: 48.17
Total Loss of Prestress Force: 8.49 Percent
Total Steel Force: 930.38 Kips
Eccentricity of Steel Force from Top of Beam: 48.52 in

## Conditions at Time = 5.0 Days

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Total Prestress Force: 904.62
Eccentricity of Prestress: 48.17
Total Loss of Prestress Force: 9.37 Percent
Total Steel Force: 921.58 Kips
Eccentricity of Steel Force from Top of Beam: 48.53 in

## Conditions at Time = 7.0 Days

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Total Prestress Force: 898.32
Eccentricity of Prestress: 48.17
Total Loss of Prestress Force: 10.01 Percent
Total Steel Force: 915.27 Kips
Eccentricity of Steel Force from Top of Beam: 48.54 in
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CONDITIONS AT TIME = 90.0 DAYS, PRIOR TO TENSIONING THE 3 STAGE OF STRANDS

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TOTAL PRESTRESS FORCE = 845.83
ECCENTRICITY OF PRESTRESS = 48.21
TOTALLOSS OF PRESTRESS FORCE = 15.26PERCENT
TOTAL STEEL FORCE = 862.79 KIPS
ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 48.60 IN

TYPE OF STEEL SURFACE : ALL BOTH
TYPE OF PRESTRESSING STRANDS : BET 7/16
NUMBER OF STRANDS : 12.0
TENSIONED TO .670 OF MAXIMUM
WOBBLE COEFFICIENT : .00020
COEFFICIENT OF FRICTION : .2500
ECCENTRICITY AT AN END : 11.50
ECCENTRICITY AT THE CENTER : 50.50
ANCHORAGE LOSS = .1875 INCH
EXTRA MOMENT = 0.000
JACKED FROM 1. END(S)

BEAM LENGTH = 103.10
CONDITIONS AT TIME = 90.0 DAYS, AFTER TENSIONING THE 3 STAGE OF STRANDS
TOTAL INITIAL PRESTRESS FORCE = 1247.44 KIPS

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TOTAL PRESTRESS FORCE = 1071.21
ECCENTRICITY OF PRESTRESS = 48.66
TOTAL LOSS OF PRESTRESS FORCE = 14.13PERCENT
TOTAL STEEL FORCE = 1092.99 KIPS
ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 48.96 IN
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| BEAM LENGTH | 103.10 |
| CONDITIONS AT TIME | 90.0 DAYS AFTER TENSIONING THE |
| TOTAL INITIAL PRESTRESS FORCE | 1491.47 KIPS |
| STRAND | YOIST | FC | FS | PRESTRESS |
| TOP | 0.00 | -0.8362 | -- | -- |
| 1 | 3.0000 | -0.8757 | 160.7600 | 166.6051 |
| 2 | 55.3000 | -1.5633 | 160.2349 | 155.7587 |
| 3 | 50.5000 | -1.5002 | 170.0724 | 166.5087 |
| 4 | 54.7500 | -1.5560 | 168.4028 | 163.9748 |
| BOTTOM | 63.00 | -1.6645 | -- | -- |
| TOTAL PRESTRESS FORCE | 1287.51 |

| ECCENTRICITY OF PRESTRESS | 49.68 |
| TOTAL LOSS OF PRESTRESS FORCE | 13.67 PERCENT |
| TOTAL STEEL FORCE | 1315.11 KIPS |

| ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM | 49.93 IN |
| TYPE OF STEEL SURFACE | ALL BOTH |
| TYPE OF PRESTRESSING STRANDS | BET 7/16 |
| NUMBER OF STRANDS | 12.0 |
| TENSIONED TO | 0.637 OF MAXIMUM |
| WOBBLE COEFFICIENT | 0.00020 |
| COEFFICIENT OF FRICTION | 0.2500 |
| ECCENTRICITY AT AN END | 35.50 |
| ECCENTRICITY AT THE CENTER | 59.00 |
| ANCHORAGE LOSS | 0.1875 INCH |
| EXTRA MOMENT | 0.000 |
| JACKED FROM 1. END(S) | |
**BEAM LENGTH = 103.10**
**CONDITIONS AT TIME = 90.0 DAYS, AFTER TENSIONING THE 5 STAGE OF STRANDS**
**TOTAL INITIAL PRESTRESS FORCE = 1728.44 KIPS**

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**TOTAL PRESTRESS FORCE = 1492.67**
**ECCENTRICITY OF PRESTRESS = 50.99**
**TOTAL LOSS OF PRESTRESS FORCE = 13.64 PERCENT**
**TOTAL STEEL FORCE = 1526.97 KIPS**
**ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 51.22 IN**

---

**CONDITIONS AT TIME = 100.0 DAYS**

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**TOTAL PRESTRESS FORCE = 1433.91**
**ECCENTRICITY OF PRESTRESS = 50.82**
**TOTAL LOSS OF PRESTRESS FORCE = 17.04 PERCENT**
**TOTAL STEEL FORCE = 1468.21 KIPS**
**ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 51.07 IN**
CONDITIONS AT TIME = 120.0 DAYS IMMEDIATELY BEFORE THE DECK IS PLACED

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TOTAL PRESTRESS FORCE = 1408.49
ECCENTRICITY OF PRESTRESS = 50.76
TOTAL LOSS OF PRESTRESS FORCE = 18.51 PERCENT
TOTAL STEEL FORCE = 1442.79 KIPS
ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 51.02 IN

COMPOSITE SECTION PROPERTIES - STARTED AT TIME = 120.0 DAYS
STRENGTH OF CONCRETE IN THE SLAB = 3500.0 PSI
STRENGTH OF CONCRETE IN THE BEAM = 5750.0 PSI
EXTRA MOMENT ADDED TO THE BEAM = 0.0 KIP-IN
TOTAL THICKNESS OF THE SLAB = 8.0 IN
STRUCTURAL THICKNESS OF THE SLAB = 7.5 INCHES
EFFECTIVE WIDTH OF THE SLAB = 84.0 IN
EXTRA MOMENT ADDED TO THE COMPOSITE SECTION = 3348.0 KIP-IN

GROSS TRANSFORMED AREA (IN²) = 1562.1
GROSS MOMENT OF INERTIA (IN⁴) = 928725.3

CONDITIONS AT TIME = 120.0 DAYS IMMEDIATELY AFTER DECK IS PLACED

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TOTAL PRESTRESS FORCE = 1400.57
ECCENTRICITY OF PRESTRESS = 50.70
TOTAL LOSS OF PRESTRESS FORCE = 18.97 PERCENT
TOTAL STEEL FORCE = 1462.25 KIPS
ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 51.14 IN

CONDITIONS AT TIME = 300.0 DAYS A COMPOSITE SECTION IS BEING USED

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TOTAL PRESTRESS FORCE = 1369.50
ECCENTRICITY OF PRESTRESS = 50.83
TOTAL LOSS OF PRESTRESS FORCE = 20.77 PERCENT
TOTAL STEEL FORCE = 1431.18 KIPS
ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 51.27 IN

CONDITIONS AT TIME = 500.0 DAYS A COMPOSITE SECTION IS BEING USED

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TOTAL PRESTRESS FORCE = 1349.12
ECCENTRICITY OF PRESTRESS = 50.84
TOTAL LOSS OF PRESTRESS FORCE = 21.95 PERCENT
TOTAL STEEL FORCE = 1410.80 KIPS
ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 51.29 IN
### Conditions at Time = 1000.0 Days

A composite section is being used.

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Total Prestress Force = 1323.54

Eccentricity of Prestress = 50.85

Total Loss of Prestress Force = 23.43 Percent

Total Steel Force = 1385.22 Kips

Eccentricity of Steel Force from Top of Beam = 51.31 in

### Conditions at Time = 3000.0 Days

A composite section is being used.

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Total Prestress Force = 1296.00

Eccentricity of Prestress = 50.88

Total Loss of Prestress Force = 25.60 Percent

Total Steel Force = 1347.69 Kips

Eccentricity of Steel Force from Top of Beam = 51.35 in
CONDITIONS AT TIME = 5000.0 DAYS A COMPOSITE SECTION IS BEING USED

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TOTAL PRESTRESS FORCE = 1269.46
ECCENTRICITY OF PRESTRESS = 50.89
TOTAL LOSS OF PRESTRESS FORCE = 26.55 PERCENT
TOTAL STEEL FORCE = 1331.14 KIPS
ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 51.37 IN

CONDITIONS AT TIME = 7300.0 DAYS A COMPOSITE SECTION IS BEING USED

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TOTAL PRESTRESS FORCE = 1257.52
ECCENTRICITY OF PRESTRESS = 50.91
TOTAL LOSS OF PRESTRESS FORCE = 27.25 PERCENT
TOTAL STEEL FORCE = 1319.20 KIPS
ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM = 51.38 IN
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**TOTAL PRESTRESS FORCE** = 1247.77
**ECCENTRICITY OF PRESTRESS** = 50.92
**TOTAL LOSS OF PRESTRESS FORCE** = 27.81 PERCENT
**TOTAL STEEL FORCE** = 1309.45 KIPS
**ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM** = 51.40 IN

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**TOTAL PRESTRESS FORCE** = 1226.87
**ECCENTRICITY OF PRESTRESS** = 50.94
**TOTAL LOSS OF PRESTRESS FORCE** = 29.02 PERCENT
**TOTAL STEEL FORCE** = 1288.55 KIPS
**ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM** = 51.42 IN
CONDITIONS AT TIME= 36500.0 DAYS A COMPOSITE SECTION IS BEING USED

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TOTAL PRESTRESS FORCE= 1209.32
ECCENTRICITY OF PRESTRESS= 50.96

TOTAL LOSS OF PRESTRESS FORCE = 30.03 PERCENT
TOTAL STEEL FORCE= 1271.00 KIPS
ECCENTRICITY OF STEEL FORCE FROM TOP OF BEAM= 51.45 IN