1974

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Recommended Citation

Tansu (Wei-Chian Chen), John, "Prediction of prestress losses for prestressed concrete members /" (1974). *Theses and Dissertations*. 4400.
https://preserve.lehigh.edu/etd/4400

PREDICTION OF PRESTRESS LOSSES
FOR PRESTRESSED CONCRETE MEMBERS

by

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A THESIS
Presented to the Graduate Committee
of Lehigh University
in Candidacy for the Degree of
Master of Science
in Civil Engineering

Lehigh University

January 1974

CERTIFICATE OF APPROVAL

This thesis is accepted and approved in partial fulfillment of the requirements of the degree of Master of Science.

January 25, 1974
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ACKNOWLEDGMENTS

The report herein, is related to the Lehigh University Project No. 339, which was conducted in Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh University. Dr. D. A. VanHorn is the Chairman of the Department. Dr. Lynn S. Beedle is the Director of the Fritz Engineering Laboratory. Dr. T. Huang is the project director.

The author sincerely appreciated and gratefully acknowledged his advisor, Dr. Ti Huang, professor in charge of the thesis and the project director of Lehigh University Project No. 382, in which the author is involved, for his supervision and patience in reviewing the author's thesis.

Sincere thanks are also due to Mrs. Ruth Grimes, who typed this manuscript, and Mr. J. M. Gera, who prepared the graphs.

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ABSTRACT

A new method of estimating the prestress losses in post-tensioned members was developed in this thesis. The method was based on the rational principles of connecting stress-strain-time relationships of the concrete and steel materials, with proper recognition to time compatibility, strain compatibility and equilibrium. A computer program, developed previously for pretensioned members, was modified to be also applicable to post-tensioned members. On account of a long assumed service life, the new method predicts a higher total final prestress loss than several existing methods. In comparison with these currently available methods, the new method provides reasonable estimates of prestress losses throughout the service life of the post-tensioned member, comparable to the PCI - General Method, but requires a much smaller calculation effort. In addition, the new method provides a direct calculation of prestress loss at any time, eliminating the need of a step-by-step procedure. Several areas of possible future improvement and refinement of the new method are suggested.

1. INTRODUCTION

1.1 Background

In spite of the rapid progress in the development of prestressed concrete as an important structural system, the estimation of prestress losses has remained a sensitive problem without a satisfactory answer. Various design specifications have included widely different provisions. Some may include tables and equations, while others specify a single member for rough approximation of these losses. However, at the present time, neither of these specifications has contributed an accurate method for estimating the prestress losses caused by many factors. This deficiency is particularly pronounced with regard to post-tensioned members.

In the past several years, an extensive study entitled "Prestress Losses in Pretensioned Concrete Structural Members" (Lehigh University Project No. 339), was conducted in Fritz Engineering Laboratory, Department of Civil Engineering, Lehigh University. The main purposes of this project were to develop a rational method for the prediction of the prestress losses for the pretensioned concrete members and to establish a practical method for this estimation. In this study, stress-strain-time relationships for concrete and steel materials were developed experimentally, and a method for the complete analysis of stress and strain conditions in pretensioned members was developed based on these relationships. Several computer programs were written to carry out the calculations as required, and to determine the prestress losses at various times during the service life of the member.

It is felt that with appropriate changes to accommodate the time sequence of post-tensioning fabrication and the strain relationships, the same basic principles used in the above-mentioned project could also be applied to post-tensioned systems.

1.2 Purpose

The main purpose of this thesis work is to develop the prediction procedure for the prestress losses in post-tensioned members, based on the experimental results and basic principles used in Lehigh University Project No. 339. In addition, it is also intended to revise the computer program developed therein so that it can be applied to both pretensioned and post-tensioned members.

1.3 Review of Problem

As mentioned in Section 1.1, an accurate method for the estimation of the prestress losses in post-tensioned members is not currently available in the codes or specification. In the Bureau of Public Roads Criteria[8] of 1954, prestress losses in post-tensioned members is estimated by the following formula:

$$\Delta_{fs} = 3000 + 11\, f_{cs} + 0.04\, f_{si}$$

where: Δ_{fs} = Loss of prestress, in psi

f_{cs} = Initial stress in concrete, at the centroid of prestressing steel, in psi

f_{si} = Initial prestress in steel, in psi

In the 1971 ACI Building Code[6], various causes of prestress losses are listed but no guidelines are given for their estimation. The PCI Committee[7] presented a step-by-step method of estimation which includes many tables and equations and involves rather lengthy calculations. In contrast, the 1969 AASHO specification[5] gave a single number of 25000 psi as an acceptable approximation. In the most recent AASHO specifications[9,10], the method for predicting the prestress losses in post-tensioned members is as follows:

$$\Delta_{fs} = 0.8\ (SH) + 0.5\ (ES) + CR_c + CR_{sp}$$

where: Δ_{fs} = Total prestress loss, excluding friction

SH = Loss due to concrete shrinkage, estimated using the following table based on the average ambient relative humidity for the geographic area.

Average Ambient Relative Humidity (percent)	SH (psi)
100 - 75	5,000
75 - 25	10,000
25 - 0	15,000

ES = Loss due to elastic shortening of concrete $\simeq 7 f_{cr}$, where f_{cr} = average concrete stress at the center of gravity of the prestressing steel at time of release.

CR_c = Loss due to creep of concrete = $16 f_{cd}$, where f_{cd} = average concrete compressive stress at the center of gravity of the prestressing steel under full dead load.

CR_{sp} = Loss of prestress due to relaxation of post-tensioning steel $\simeq 20{,}000 - 0.125\ [0.8\ (SH) + 0.5\ (ES) + CR_c]$

The presence of such a diversity of methods for the same purpose attests to the fact that no one method is fully rational and suitable for engineering application.

In Lehigh University Project No. 339, a number of factors which influence the prestress loss were first studied, such as concrete mixture, concrete stress level, concrete stress gradient, etc. Numerous specimens have been tested in order to determine the characteristics of relaxation, elastic shortening, shrinkage and creep of the concrete and steel materials. The test results were carefully analyzed to determine the characteristics of the materials. The stress-strain-time relationships of the concrete and steel materials were then established. In order to develop the prediction formulas for the prestress loss, three sets of conditions, namely, time compatibility, strain compatibility and equilibrium of stresses were applied to link the stress-strain-time relationships of the concrete and steel materials. In addition, the concrete stress was assumed to vary linearly across the depth of the concrete section. These conditions were found to be sufficient to completely determine the stresses and the strains in concrete and steel for any given time.

For the post-tensioned members, the casting of concrete precedes the tensioning of the strands, while for the pretensioned members, the tensioning of the strands is carried out first and then followed by the placement of concrete. The difference in the fabrication procedures of these two structural systems naturally causes differences in their prestress loss behaviors. In this thesis, it is intended to examine these differences, to make appropriate modifications to the procedure previously developed for pretensioned members, and to develop procedures for the prediction of prestress losses in post-tensioned concrete members.

2. POST-TENSIONING VS. PRETENSIONING

2.1 Differences in Fabrication Procedure

As stated in the preceding chapter, it is desired to modify the procedures previously developed for prestress losses in pretensioned concrete members, so that they can be applied to post-tensioned members as well. Before proceeding with the derivations, it is appropriate to point out the differences between pretensioning and post-tensioning. A brief description of these two processes is given in the following paragraph.

Pretensioning refers to the stretching of the strands before the placing of concrete. In this process, the strands are first anchored temporarily to the prestressing bed. After concrete has been placed and become hardened, the strands are released from the bed and the prestress is transferred to concrete. Pretensioned members are usually fabricated in the prestressing plants where permanent prestressing facilities are provided, but they can also be fabricated in the field. Post-tensioning refers to the stretching of the strands after the placing and the hardening of concrete have been achieved. No temporary anchorage is needed, and tensioning is done directly against hardened concrete. The most important distinction between pretensioning and post-tensioning is in the above-mentioned order of the several fabrication operations. This difference causes important differences in the prestress loss behaviors. For instance, for the pretensioned member, the concrete is usually stressed at an earlier stage than that for the post-tensioned member, resulting in higher losses attributed to concrete strains. On the other hand, friction and anchorage losses are usually more important in post-tensioned members on account of the shorter tendon lengths, and higher friction coefficients.

2.2 Definitions of Prestress and Losses

Before the discussion of the differences in prestress losses is given, it is necessary to define the terms "Prestress" and "Losses" properly so that no misunderstanding will arise concerning the meaning of these two terms as they appear in this thesis.

Prestress: Prestress is defined to be the stress introduced in concrete or steel prior to the application of loads. At a given time after transfer, the prestress is defined as the stress remaining in the material if all applied loads, including the weight of the member, were temporarily removed (Ref. 3). If the strands in the pretensioned member are straight, the prestress is constant throughout the length of the member initially, but variation gradually develops on account of concrete creep caused by the varying stresses caused by loads. In post-tensioned members, the prestressing force varies along the length of the member because of the presence of anchorage and friction losses. In both cases, the prestress is different from section to section, and must be defined with reference to the specific section.

Losses: For pretensioned members, losses of prestress are evaluated with reference to the initial tensioning stresses in the steel elements as existing upon anchorage to the prestressing bed (Ref. 3). For post-tensioned members wherein tendons are stretched sequentially, the "initial prestress" value is defined as the average of the initial tensioning stress in each tendon upon anchorage. As the tensioning of each tendon causes elastic loss in each of the preceding tendons, the above-defined "initial prestress" condition never really exists. It is chosen as the basis of reference because the steel stress is usually controlled only at the tensioning stage. Of course, for systems where all tendons are stretched at once, the initial condition defined would be the condition immediately after anchorage. Although the prestress is defined for each section of a post-tensioned member, it is customary to refer to the initial prestress at the jacking end for prestress losses, so that the friction and anchorage losses can be accounted for. This reference frame will be used in this study. However, only the elastic, creep, shrinkage and relaxation losses will be considered. The inclusion of friction and anchorage losses is left for future time.

2.3 Components of Prestress Losses

The different fabrication procedures used for pre- and post-tensioned members lead to significant differences in the prestress loss characteristics. In the following, these differences will be discussed with reference to each one of the several major components of prestress losses.

Friction Loss: Loss of prestress due to the contact friction between the tendon and the surrounding material. The friction loss for both the pretensioned and the post-tensioned members occurs at the time of tensioning. For the pretensioned member, this loss is negligibly small, existing only if tendons are deflected. The post-tensioned member will suffer greater loss due to the sliding of the tendon against concrete over the whole length. Also, it exists whether the tendons are straight or draped. Theory for the estimation of this loss has been well established and it can be exactly considered in the design (Ref. 4). This is not time-dependent.

Anchorage Deformation: Loss of prestress due to the anchorage deformation. This loss occurs when the tensioning force of the tendon is transmitted from the jack to the anchorage system. In general, the post-tensioned member will suffer greater anchorage loss, since this loss would have to be distributed over a shorter length. Similarly to frictional losses, this loss can be theoretically determined and it is not time-dependent (Ref. 4).

Relaxation Loss: Strictly speaking, relaxation refers to the loss of stress in the tendon which is held at a constant strain for a period of time. In a real prestressed concrete member, the strain in steel gradually decreases on account of the creep and shrinkage of concrete. Relaxation in the context of prestress losses is defined to represent the loss of prestress unaccounted for by the elastic response to strain changes. For both pretensioned and post-tensioned systems, relaxation loss starts from the tensioning time. However, a difference exists with reference to the transfer time. In pretensioned systems, a part of relaxation loss takes place before transfer under a pure relaxation condition. In post-tensioned systems, transfer takes place at tensioning time, hence there is no pre-transfer relaxation.

Shrinkage Loss: The loss of prestress due to shrinkage of concrete. This is caused by the loss of moisture content from concrete on account of the environmental factors such as high temperature, low relative humidity, etc. The shrinkage of concrete starts as soon as the curing stops, whether pretensioning or post-tensioning is involved. However, an important difference exists between the losses caused by shrinkage in these two types of structural systems. In pretensioned members, all shrinkage of concrete causes loss of prestress. In contrast, in a post-tensioned system, the shrinkage of concrete occurring before stretching causes no loss of prestress. Consequently, while the same time function for shrinkage strain can be used for post-tensioned as for pretensioned systems, the shrinkage occurring before the post-tensioning must be deducted for the purpose of estimating prestress losses.

Elastic Shortening Loss: The loss of prestress due to the elastic shortening of concrete takes place at the time of transfer. In pretensioned members, concrete is bonded to tensioned steel before transfer and the elastic shortening in concrete at transfer always causes a loss in prestress. For post-tensioned members, the concrete shortens as the tendons are being stretched. If the member has only one single tendon or if all tendons are stretched simultaneously, no loss in prestress due to elastic shortening will occur because the force in the tendon is measured after the elastic shortening of the concrete has taken place. However, if there is more than one tendon in the member and they are stressed in sequence, the loss of prestress due to elastic shortening will be different for each tendon. The first tendon will suffer the largest amount of loss due to the shortening of concrete by the subsequent application of prestress from all other tendons. The last one will suffer no loss since all that shortening will have taken place before it is measured (Ref. 4). Instead of calculating the elastic loss for each tendon separately, a reasonable approximation has been made in this thesis (see Section 3.2.2).

Creep Loss: Loss of prestress due to the change of the strain in concrete under constant stress. The occurrence of the creep loss for both the pretensioned and the post-tensioned members are in the same time period, namely, after the transfer of prestress, and the same expressions will be used. Similar to relaxation, the actual condition in prestressed concrete is not that of a constant strain, and the creep strain is interpreted broadly to mean the concrete strain not directly reflected by elastic response to stress, nor by shrinkage.

3. DERIVATION OF PROCEDURE

3.1 Procedure for Pretensioned Systems

A brief summary of the derivation of the procedures for the prediction of the prestress losses in pretensioned members, as developed in Lehigh University Project No. 339, will be given in this section[1,3].

The stress-strain-time relationships of the steel and concrete materials, as derived from the experimental data, are as follows:

$$\begin{aligned} f_s = f_{pu}\{&A_1 + A_2 S_s + A_3 S_s^2 \\ &- [B_1 + B_2 \log(t_s + 1)]\, S_s - [B_3 + B_4 \log(t_s + 1)]\, S_s^2\} \end{aligned} \quad (3\text{-}1)$$

$$\begin{aligned} S_c = C_1 f_c &+ [D_1 + D_2 \log(t_c + 1)] \\ &+ \{[E_1 + E_2 \log(t_c + 1)] + f_c\,[E_3 + E_4 \log(t_c + 1)]\} \end{aligned} \quad (3\text{-}2)$$

where: f_s = Steel stress, in ksi

f_{pu} = Specified ultimate tensile strength of steel, in ksi

S_s = Steel strain, in 10^{-2} in./in.

A_1, A_2, A_3 = Regression coefficients of stress-strain curve of steel

B_1, B_2, B_3, B_4 = Regression coefficients of relaxation of steel

t_s = Steel time, starting from initial tensioning, in days

S_c = Concrete strain, in 10^{-2} in./in.

f_c = Concrete stress, in ksi

C_1 = $100/E_c$, coefficient for concrete strain due to elastic shortening

D_1, D_2 = Regression coefficients for concrete strain due to shrinkage

E_1, E_2, E_3, E_4 = Regression coefficients for concrete strain due to creep

t_c = Concrete time, starting from the time of transfer, taken as the same as the end of curing period, in days

Tables 1 and 2 show the experimental values of regression coefficients A's, B's, C1, D's and E's, respectively.

For the linkage of the stress-strain-time surfaces of the concrete and steel materials, the following three sets of conditions were used:

(1) Time compatibility

$$t_s - t_c = k_1 \qquad (3\text{-}3)$$

(2) Strain compatibility, at the location of each prestressing strand

$$S_s + S_c = k_2 \qquad (3\text{-}4)$$

(3) Equilibrium conditions

$$\int f_c \, dA_c - \Sigma f_s a_{ps} = P \qquad (3\text{-}5)$$

$$\int f_c x \, dA_c - \Sigma f_s x a_{ps} = -M \qquad (3\text{-}6)$$

where: k_1 = Time interval from tensioning of steel to transfer of prestress, in days (this includes the time for form setting, casting, and curing)

k_2 = Initial tensioning strain in steel, in 10^{-2} in./in.

A_c = Area of net concrete section, in in.^{2}

a_{ps} = Area of individual prestressing elements, in in.^{2}

x = Distance to elementary area from the centroidal horizontal axis of A_c, in in.

P = Applied axial load on section, in kips

M = Applied bending moment on section, in kip-in.

The sign conventions for the positive directions of P, M, and x are shown in Fig. 1. All of the parameters used in Eqs. 3-3 to 3-6 are either known quantities or can be specified in the design. For Eqs. 3-5 and 3-6, the integrations are over the entire net concrete area, and the summations are over all pretensioning elements. In addition to the linking conditions (3-3) to (3-6), an assumption was made that the concrete stress varies linearly across the depth of the concrete section,

$$f_c = g_1 + g_2 x \tag{3-7}$$

In order to facilitate further derivation, a group of parameters are introduced for Eqs. 3-1 and 3-2, respectively.

$$P_1 = A_1 f_{pu}$$

$$P_2 = [A_2 - B_1 - B_2 \log (t_s + 1)] \; f_{pu}$$

$$P_3 = [A_3 - B_3 - B_4 \log (t_s + 1)] \; f_{pu}$$

$$Q_1 = D_1 + E_1 + (D_2 + E_2) \log (t_c + 1)$$

$$Q_2 = C_1 + E_3 + E_4 \log (t_c + 1)$$

Then $$f_s = P_1 + P_2 S_s + P_3 S_s^2 \qquad (3\text{-}8)$$

$$S_c = Q_1 + Q_2 f_c \qquad (3\text{-}9)$$

Substituting Eq. 3-9 into Eq. 3-4

$$S_s = k_2 - Q_1 - Q_2 f_{cs} \qquad (3\text{-}10)$$

Substituting Eq. 3-10 into Eq. 3-8

$$f_s = P_1 + P_2 \; (k_2 - Q_1 - Q_2 f_{cs}) + P_3 \; (k_2 - Q_1 - Q_2 f_{cs})^2$$

$$= R_1 + R_2 f_{cs} + R_3 f_{cs}^2 \qquad (3\text{-}11)$$

where: $$R_1 = P_1 + P_2 \; (k_2 - Q_1) + P_3 \; (k_2 - Q_1)^2 \qquad (3\text{-}12)$$

$$R_2 = -Q_2 \; [P_2 + 2P_3 \; (k_2 - Q_1)] \qquad (3\text{-}13)$$

$$R_3 = P_3 Q_2^2 \qquad (3\text{-}14)$$

Combining Eqs. 3-5, 3-6, 3-7, and 3-11, the following two simultaneous quadratic equations can be derived:

$$\left.\begin{aligned} U_1 + U_2 g_1 + U_3 g_2 + U_4 g_1^2 + U_5 g_1 g_2 + U_6 g_2^2 = 0 \\ V_1 + V_2 g_1 + V_3 g_2 + V_4 g_1^2 + V_5 g_1 g_2 + V_6 g_2^2 = 0 \end{aligned}\right\} \qquad (3\text{-}15)$$

where:

$$\begin{aligned} U_1 &= R_1 A_{ps} + P & \qquad V_1 &= R_1 \Sigma x a_{ps} - M \\ U_2 &= (R_2 + 1)\, A_{ps} - A_g & V_2 &= (R_2 + 1)\, \Sigma x a_{ps} = U_3 \\ U_3 &= (R_2 + 1)\, \Sigma x a_{ps} & V_3 &= (R_2 + 1)\, \Sigma x^2 a_{ps} - I_g \\ U_4 &= R_3 A_{ps} & V_4 &= R_3 \Sigma x a_{ps} = \frac{1}{2} U_5 \\ U_5 &= 2R_3 \Sigma x a_{ps} & V_5 &= 2R_3 \Sigma x^2 a_{ps} = 2U_6 \\ U_6 &= R_3 \Sigma x^2 a_{ps} & V_6 &= R_3 \Sigma x^3 a_{ps} \end{aligned}$$

For a given pretensioned member, the parameters U and V are determinable for any assigned time t_c, and g_1, g_2 can be solved from Eq. 3-15. In this manner, concrete stress distribution is completely determined.

It has been found that neglecting the spread of steel in the section causes only negligible errors in the total steel force ($A_{ps} f_s$). Therefore, for practicality and simplicity, prestressing steel is assumed to be concentrated at one point, the c.g.s. (Ref. 3). With this simplification, Eqs. 3-15 can be reduced to a single quadratic equation, as follows:

$$(R_1 - \beta f'_{c\ell}) + (R_2 - \beta + 1)\, f_{cs} + R_3 f_{cs}^2 = 0 \qquad (3\text{-}16)$$

where: f_{cs} = Concrete fiber stress at c.g.s., in ksi

$(= g_1 + g_2 e_g)$

$f'_{c\ell}$ = Nominal concrete fiber stress at c.g.s. caused by applied loads

$$= -\frac{P}{A_g} + \frac{Me_g}{I_g} \text{ (tension positive)}$$

β = A dimensionless geometrical parameter

$$= \frac{1}{A_{ps}\left(\frac{1}{A_g} + \frac{e_g^2}{I_g}\right)} = \frac{A_g I_g}{A_{ps}\ (I_g + A_g e_g^2)}$$

where: A_g = Area of gross cross section, in sq. in.

I_g = Moment of inertia of gross cross section, in in.^{4}

e_g = Eccentricity of prestress with reference to gross cross section, in in.

A_{ps} = Total area of prestressing steel, in sq. in.

The steel stress at any arbitrary time can be obtained by adding Eqs. 3-16 and 3-11 together.

$$f_s = (\beta - 1)\ f_{cs} + \beta\ f'_{c\ell} \tag{3-17}$$

Further details of the development of the stress-strain-time relationships of the concrete and steel materials and the derivation of the procedures for the prediction formulas can be found in Fritz Engineering Laboratory Reports No. 339.6[2], 339.7[1] and 339.9[3].

The basic procedures for the calculation of prestress losses in pretensioned members can be summarized as follows:

(1) Material, geometry and fabrication parameters are known or specified for the problem. (These include the steel and concrete materials, β, $f'_{c\ell}$, k_1 and k_2.)

(2) Compute R_1, R_2 and R_3 for arbitrary time t_c with the application of Eqs. 3-12, 3-13 and 3-14.

(3) Solve Eq. 3-16 for f_{cs}.

(4) Compute the steel stress f_s by Eq. 3-17.

(5) With Eqs. 3-2 and 3-4, concrete and steel strains, S_c and S_s, can be determined.

To facilitate further discussion and the understanding of the computer program "PRELOC", which performs the above calculating procedures, several key stages for the life of the pretensioned member are given as follows:

Stage 1: Initial tensioning (after anchoring to abutments), $t_s = 0$.

Stage 2: Immediately before transfer, $t_s = k_1$.

Stage 3: Immediately after transfer, $t_s = k_1$, $t_c = 0$.

Stage 4: Immediately before application of loads, $P = M = 0$.

Stage 5: Immediately after application of loads, $p \neq 0$ and/or $M \neq 0$.

Stage 6: End of service life, taken as 100 years after transfer, $t_c = 36500$.

Fig. 3 shows the typical variation of f_s through the six stages. Two auxiliary stress variations are also shown in this figure. The curve 3-6* or 3*-6* refers to a totally unloaded member, and the curve 3**-6** represents the case where the external loads are applied at the time of transfer. By the nature of the concrete and steel surfaces, point 5 falls on curve 3**-6**, and the curve 5-6 coincides with 5-6** (Ref. 3).

3.2 Procedure for Post-Tensioned Systems

3.2.1 Stress-Strain-Time Relationship

The stress-strain-time relationship of steel for the post-tensioned member is exactly the same as the one used for the pretensioned member, since, for both kinds of prestressed member, relaxation loss will occur after the initial tensioning of the strand, as mentioned earlier in Chapter 2 and the steel time, t_s, should be considered as the time starting from the initial tensioning of the strand. Hence, the following equation will be applied for the post-tensioned member:

$$
\begin{aligned}
f_s = f_{pu} \{ & A_1 + A_2 S_s + A_3 S_s^2 \\
& - [B_1 + B_2 \log (t_s + 1)]\, S_s - [B_3 + B_4 \log (t_s + 1)]\, S_s^2 \} \qquad (3\text{-}1)
\end{aligned}
$$

All parameters used above and those, which will be used later in this chapter, will have the same meanings as those used for the pretensioned member unless otherwise specified.

A change must be made in the stress-strain-time relationship of concrete with regard to the creep component of the concrete strain. For the pretensioned member, creep loss starts after the transfer of prestress, which is preceded by the fabrication of the concrete specimen. The duration between the end of the curing period and the transfer of prestress is very short. In addition, the shrinkage loss prior to prestress transfer causes loss in prestress (see Section 2.3). Hence, the same time value, t_c, measured from the end of curing, was used for both shrinkage and creep. For the post-tensioned member, the prestressing of concrete occurs at the time when steel is tensioned, but usually significantly later than the end of curing. On the other hand, shrinkage strain will start to develop as soon as the curing is stopped. Although the shrinkage of concrete prior to post-tensioning causes no loss in prestress, it must be included in the total concrete strain if the previous stress-strain-time relationship of concrete is to be used. Therefore, the following equation is used for the stress-strain-time relationship of concrete for the post-tensioned member:

$$\begin{aligned} S_c = {} & C_1 f_c + [D_1 + D_2 \log (t_c + 1)] \\ & + \{[E_1 + E_2 \log (t_s + 1)] + f_c\,[E_3 + E_4 \log (t_s + 1)]\} \qquad (3\text{-}18) \end{aligned}$$

3.2.2 Linking Conditions

Three sets of conditions were used for the linkage of the stress-strain-time relationships of the concrete and steel materials.

(a) Time compatibility: For the pretensioned member, the steel time, t_s, starts after the initial tensioning of the strand and the concrete time, t_c, starts at the end of curing, and t_s precedes t_c as shown in Fig. 3. This is on account of the precedence of the tensioning of the strands to the placement of concrete. For post-tensioned members, the reverse is true, as t_c is started before t_s, as shown in Fig. 4. This is because the fabrication of the concrete specimen precedes the tensioning of the strands. Therefore, the time compatibility condition for post-tensioned members is

$$t_c - t_s = k_3 \tag{3-19}$$

where: k_3 = Time interval from the end of curing period to post-tensioning, in days

(b) Strain compatibility: For the pretensioned member, there is no concrete strain and concrete stress prior to the transfer of prestress because the tension in steel strands is resisted by the prestressing bed. And as the concrete is hardened around tensioned steel, the strain compatibility is maintained from the time before transfer, resulting in Eq. 3-4. For post-tensioned members, the materials are not bonded together until the post-tensioning has been completed, and the compatibility of strains also is not in effect until this time. In consequence, the shrinkage strain occurring before post-tensioning must be considered in this linking condition. In addition, during the process of tensioning, the tendon is jacked against the concrete and in some cases, the tendons are jacked in sequence. As concrete shortens simultaneously as steel is being stretched, the concrete strain due to elastic shortening of concrete should also be taken into account. The following equation of strain compatibility is used for the post-tensioned member:

$$S_s + S_c = k_4 \qquad (3\text{-}20)$$

where: k_4 = Sum of concrete and steel strains at c.g.s. immediately after post-tensioning, in 10^{-2} in./in.

$= D_1 + D_2 \log (k_3 + 1) + k_2 + (1 - \alpha)\, C_1 f_{c_3}$

f_{c_3} = Concrete prestress at c.g.s. immediately after post-tensioning, in ksi, to be calculated by a step-by-step procedure described on pp. 23 and 24.

k_2 = Initial tensioning strain in steel at the end of the member after friction loss and anchorage loss have been considered, in 10^{-2} in./in.

$$\alpha = \frac{Scel_{avg}}{C_1 f_{c_3}}$$

= Fraction reflecting the elastic shortening loss of prestress

= 1 if pretensioned member

= $0 - \frac{1}{2}$ if post-tensioned is done in a single stage

$Scel_{avg}$ = Average elastic shortening of prestressing steel due to the sequential stretching of strands

In this thesis, $\alpha = \frac{1}{2}$ will be used for the estimation of the elastic loss due to the sequential stretching of strands.

The step-by-step procedure for calculating f_{c_3} is described as follows: At each stage of the sequential stretching of strands, the tensioning of strands being stretched is resisted by the net concrete section combined with all the strands already anchored during preceding stages. Hence:

$$f_{c_3(i)} = N_{s(i)} \; a_{ps} \; f_{s_2} \left(\frac{1}{A_{t(i)}} + \frac{e^2_{t(i)}}{I_{t(i)}} \right)$$

where: $N_{s(i)}$ = The number of strands being stretched at the i^{th} stage

$f_{s_2} = f_{si}$ = Steel stress immediately after anchorage, in ksi

$A_{t(i)}$ = Area of the i^{th} transformed cross section, including the area of the net concrete section and the area of the strands anchored during all previous steps {up to the $(i-1)^{th}$}, in sq. in.

$e_{t(i)}$ = Eccentricity of steel from centroid of the i^{th} transformed cross section, in inches

$I_{t(i)}$ = Moment of inertia of the i^{th} transformed cross section, in in.^{4}

Therefore: $f_{c_3} = \sum_{i=1}^{N} N_{s(i)}\, a_{ps}\, f_{s_2} \left(\frac{1}{A_{t(i)}} + \frac{e^2_{t(i)}}{I_{t(i)}} \right)$

(c) <u>Equilibrium conditions</u>: The equilibrium equations for the post-tensioned member are the same as those for the pretensioned member:

$$\int f_c dA_c - \Sigma f_s a_{ps} = P \qquad (3\text{-}5)$$

$$\int f_c x dA_c - \Sigma f_s x a_{ps} = -M \qquad (3\text{-}6)$$

The sign conventions for P, M, and x are also the same as those adopted for pretensioned members.

(d) <u>Linear stress distribution</u>: As for pretensioned members, the assumption was made that the concrete stress varies linearly across the depth of the concrete section.

$$f_c = g_1 + g_2 x \qquad (3\text{-}7)$$

3.2.3 Basic Procedure

Eqs. 3-1, 3-18, 3-19, 3-20, 3-5, 3-6 and 3-7 will now be combined to form the basic relationship for the analysis of a post-tensioned member.

Substituting Eq. 3-7 into Eqs. 3-5 and 3-6 and performing the integrations

$$A_g g_1 - \Sigma\,(f_s + f_{cs})\,a_{ps} = P \qquad (3\text{-}5a)$$

$$I_g g_2 - \Sigma\,(f_s + f_{cs})\,x_s a_{ps} = -M \qquad (3\text{-}6a)$$

where: x_s = x distance for an individual prestressing element, in in.

Eq. 3-7 can be written as follows:

$$f_{cs} = g_1 + g_2 x_s \qquad (3\text{-}7a)$$

In order to avoid lengthy mathematical expressions in the derivations, a group of parameters are introduced in Eqs. 3-1 and 3-18. The parameters P_1, P_2 and P_3 are exactly the same as those used for pre-tensioned members (Eq. 3-8). The parameters Q_1 and Q_2 are redefined:

$$Q_1 = D_1 + E_1 + D_2 \log\,(t_c + 1) + E_2 \log\,(t_s + 1)$$

$$Q_2 = C_1 + E_3 + E_4 \log\,(t_s + 1)$$

Therefore: $f_s = P_1 + P_2 S_s + P_3 S_s^2$ (3-8)

$$S_c = Q_1 + Q_2 f_c \qquad (3\text{-}21)$$

Substituting Eq. 3-21 into Eq. 3-20

$$S_s = k_4 - Q_1 - Q_2 f_{cs} \tag{3-22}$$

Substituting Eq. 3-22 into Eq. 3-8

$$f_s = P_1 + P_2 (k_4 - Q_1 - Q_2 f_{cs}) + P_3 (k_4 - Q_1 - Q_2 f_{cs})^2$$

$$= R_1 + R_2 f_{cs} + R_3 f_{cs}^2 \tag{3-23}$$

where: $R_1 = P_1 + P_2 (k_4 - Q_1) + P_3 (k_4 - Q_1)^2$ (3-24)

$$R_2 = -Q_2 [P_2 + 2P_3 (k_4 - Q_1)] \tag{3-25}$$

$$R_3 = P_3 Q_2^2 \tag{3-26}$$

It should be noted that the parameters R_1, R_2 and R_3 in Eq. 3-23 are different from those used in Eq. 3-11.

As mentioned earlier in Section 3.1, the prestressing steel can be assumed to be concentrated at one point, the c.g.s. (Ref. 3). Therefore Eqs. 3-5a and 3-6a can be written as follows:

$$A_g g_1 - (f_s + f_{cs}) A_{ps} = P \tag{3-5b}$$

$$I_g g_2 - (f_s + f_{cs}) e_g A_{ps} = -M \tag{3-6b}$$

Also $f_{cs} = g_1 + g_2 e_g$ (3-7b)

Substituting Eq. 3-7b into 3-23

$$f_s = R_1 + R_2 (g_1 + g_2 e_g) + R_3 (g_1 + g_2 e_g)^2 \tag{3-27}$$

Substituting Eqs. 3-7b and 3-27 into Eqs. 3-5b and 3-6b

$$A_g g_1 - [R_1 + (R_2 + 1)\ (g_1 + g_2 e_g) + R_3\ (g_1 + g_2 e_g)^2]\ A_{ps} = P \qquad (3\text{-}28)$$

$$I_g g_2 - [R_1 + (R_2 + 1)\ (g_1 + g_2 e_g) + R_3\ (g_1 + g_2 e_g)^2]\ A_{ps} e_g = -M \qquad (3\text{-}29)$$

Multiply Eq. 3-28 by e_g and subtracting Eq. 3-29, the following equation can be obtained.

$$(Pe_g + M) - (A_g e_g)\ g_1 + I_g g_2 = 0$$

$$g_2 = \frac{A_g e_g}{I_g}\ g_1 - \frac{Pe_g + M}{I_g} \qquad (3\text{-}30)$$

Substituting Eq. 3-30 into Eq. 3-28, the following equation can be obtained

$$W_1 + W_2 g_1 + W_3 g_1^2 = 0 \qquad (3\text{-}31)$$

where:

$$W_1 = R_1 A_{ps} + P - (R_2 + 1)\ A_{ps} e_g \left(\frac{Pe_g + M}{I_g} \right) + R_3 A_{ps} e_g^2 \left(- \frac{Pe_g + M}{I_g} \right)^2$$

$$W_2 = \left[(R_2 + 1)\ A_{ps} - 2R_3 A_{ps} e_g \left(\frac{Pe_g + M}{I_g} \right) \right] \left(\frac{A_g e_g^2}{I_g} + 1 \right) - A_g$$

$$W_3 = R_3 A_{ps} \left(\frac{A_g^2 e_g^4}{I_g^2} + 2\,\frac{A_g e_g^2}{I_g} + 1 \right)$$

With Eqs. 3-30 and 3-31, the constants g_1 and g_2 can be solved. The concrete stresses and strains can be calculated by using Eqs. 3-7 and 3-21. Steel stress is computed by using Eq. 3-23.

Alternatively, concrete stress at centroid of steel, f_{cs}, can be determined directly without first solving for g_1 and g_2. Multiply Eq. 3-28 by I_g, Eq. 3-29 by $(A_g e_g)$, add these two equations and substitute Eq. 3-7b.

$$A_g I_g f_{cs} - [R_1 + (R_2 + 1) f_{cs} + R_3 f_{cs}^2] (I_g + A_g e_g^2) A_{ps} = P I_g - M A_g e_g$$

$$f_{cs} - [R_1 + (R_2 + 1) f_{cs} + R_3 f_{cs}^2] \left(\frac{1}{A_g} + \frac{e_g^2}{I_g}\right) A_{ps} = \frac{P}{A_g} - \frac{M e_g}{I_g} \qquad (3\text{-}32)$$

Introducing the same parameters β and $f'_{c\ell}$ as those for pretensioned member, then Eq. 3-32 becomes

$$(R_1 - \beta f'_{c\ell}) + (R_2 - \beta + 1) f_{cs} + R_3 f_{cs}^2 = 0 \qquad (3\text{-}32a)$$

After solving for f_{cs} from Eq. 3-32a, steel stress can be easily calculated by using Eq. 3-23. Concrete stresses at other locations, if desired, can then be calculated by simple equilibrium. In the computer subroutine PRED1 (see Chapter 4), the more direct algorithm of solving for g_1 and g_2 was used.

Neglecting the third term of Eq. 3-32a since it is generally several orders of magnitude smaller than the other two terms:

$$(R_1 - \beta f'_{c\ell}) + (R_2 - \beta + 1)\, f_{cs} = 0 \tag{3-33}$$

$$f_{cs} = \frac{R_1 - \beta f'_{c\ell}}{\beta - R_2 - 1}$$

Adding Eq. 3-32a with Eq. 3-23

$$f_s = (\beta - 1)\, f_{cs} + \beta f'_{c\ell} \tag{3-34}$$

The basic procedures for the calculation of prestress losses in post-tensioned members are essentially the same as those used for pretensioned members. They are described as follows:

(1) Material, geometry and fabrication parameters are known or specified for the problem. (These include the steel and concrete materials, β, $f'_{c\ell}$, k_2 and k_3.)

(2) Calculate f_{c3} (see section 3.2.2) and k_4.

(3) For any specified time, calculate P_1, P_2, P_3, Q_1 and Q_2. Then, R_1, R_2 and R_3 are calculated from Eqs. 3-24, 3-25 and 3-26.

(4) Solve Eq. 3-32a for f_{cs}.

(5) Compute the steel stress f_s with the application of Eq. 3-34.

(6) With Eqs. 3-18 or 3-21 and 3-20, determine concrete and steel strains, S_c and S_s.

Computer program "PRELOSS" is written to carry out these claculations. Its details are given in the next chapter.

In order to facilitate further discussion, several key stages of a post-tensioned member are identified as follows:

Stage 1: The beginning of the fabrication of concrete specimen, $t_c = 0$.

Stage 2: Fictitious stage for the initial tensioning of each strand, $t_c = k_3$, $t_s = 0$, $S_s = k_2$, $S_c = 0$.

Stage 3: Immediately after completion of post-tensioning, $t_c = k_3$, $t_s = 0$, $S_s + S_c = k_4$.

Stage 4: Immediately before application of loads, $P = M = 0$.

Stage 5: Immediately after application of loads, $P \neq 0$ and/or $M \neq 0$.

Stage 6: End of service life, taken as 100 years after post-tensioning, $t_s = 36500$.

The typical variation of steel stress through these six stages is shown in Fig. 4. The curves 3-6* or 3*-6* and 3**-6** are defined with the same meanings as those for pretensioned members.

Comparing the steel stress variations for pretensioned and post-tensioned members (Figs. 3 and 4), a fundamental difference between the second stages should be noted. In pretensioned members, stage 2 is real and exists just prior to transfer. In post-tensioned members, stage 2 is an imaginary one, with all tendons stretched to the prescribed strain k_2, but no strain in concrete. This situation obviously does not occur in post-tensioned members, but is used here only for convenience of formulation.

4. PROGRAM "PRELOSS"

In order to facilitate the calculations of the prestress losses, with the application of the prediction formulas developed for post-tensioned members (see Chapter 3), the computer program "PRELOC", which was written for the calculations of prestress losses in pretensioned members only, was revised so that the prestress losses in both pretensioned and post-tensioned members can be computed. The revised program is named "PRELOSS".

A brief description of the main program and of each subroutine will be given in the following paragraphs.

Main Program: It controls the main flow of operations. Referring to the flow chart in the Appendix, the input data includes the stress-strain-time relationships of the steel and concrete materials, type of the strand, an index indicating pretensioned member or post-tensioned member, the total number of the strands, the geometrical properties of the cross section, the eccentricity of prestress, the initial stress (or strain) of the strand, the time interval from tensioning of steel to transfer of prestress for pretensioned members or that from the end of curing period to post-tensioning for post-tensioned members, the magnitude and time of applied loads (and moment), and in some cases, selected levels where concrete stress and strain information is desired. The function of this program is to call the several subrountines INITI, ELASHO, POINT, and ACTPATH to carry out the calculations needed.

Subroutine INITI: Called by the main program, this subroutine sets up the entire problem and completes information at the initial time (at stage 1 for pretensioned members and stage 2 for post-tensioned members, see pp. 18 and 29). From a data bank, this subroutine selects the regression coefficients for the stress-strain-time relationships of the given concrete and steel materials (see Chapter 3), the standard ages for concrete (or steel) when prestress losses are to be computed, the strand properties, and defines the several key stages in the life of the member (Figs. 3 and 4). This subroutine, also defines a number of variables used for output purposes. After initializing, this program calculates the standard ages for steel if pretensioned members or for concrete if post-tensioned members, the total area of strands, the ultimate strength of the strand and calls subrountine SURST to calculate the initial steel stress or strain, whichever is not given.

Subroutine SURST: This subroutine contains the stress-strain-time relationship of steel, and is called by subroutines INITI and POINT. If the stress is known, this subroutine is entered as entry SSS to calculate the strain. If the strain is known, it is entered as entry FFF to calculate the stress.

Subroutine ELASHO: This subroutine is provided for post-tensioned members only. It calculates the concrete stress at c.g.s. immediately upon post-tensioning when the tendons are stretched. It also evaluates the parameter k_4.

Subroutine POINT: This subroutine provides the initialization of time for steel and concrete at each key stage and the auxiliary stages. It uses the subroutines PREDI, SURST and PRECS to calculate the stress and strain conditions in concrete and steel at the several key stages of the service life of the member. In addition, this subroutine also computes, for each key stage as well as each auxiliary stage, the loss of prestress with reference to the initial stress, and the percentage loss.

Subroutine PREDI: Called by subroutines POINT, ACTPATH and ALTPATH, this subroutine performs the basic prediction calculations as described in Chapter 3. It solves the quadratic equation (3-31) for the parameter g_1, and evaluates g_2 by Eq. 3-30. Concrete stresses and strains at the top, centroid, c.g.s. and bottom fibers of concrete gross section are then calculated by using Eqs. 3-7 and 3-9 or 3-21. With the application of strain compatibility relationship for concrete and steel, steel strain can be obtained and steel stress is then calculated by using either Eq. 3-11 or Eq. 3-23.

Subroutine PRECS: Called out from subroutines POINT and ACTPATH, it uses the g_1 and g_2 values obtained from subroutine PREDI and calculates concrete stresses and strains at selected levels (up to 5 levels) with the application of Eqs. 3-7 and 3-9 or 3-21.

Subroutine ACTPATH: Called by the main program. Referring to Figs. 3 and 4, this subroutine calculates the growth of prestress losses along the loading path 3-6. Hence, the prestress loss with reference to the initial steel stress, percentages of losses in terms of the initial steel stress and of the total loss for the service life of 100 years, at each key stage and each pre-selected age (up to 22 ages) are calculated. It calls out subroutine PREDI to compute stress and strain for steel and concrete at each key stage as well as each standard age. Similarly, loss of prestress with reference to steel stress immediately after prestressing of concrete, percentages of losses in terms of initial steel stress and of the total loss with reference to the steel stress immediately after prestressing of concrete are also calculated. In addition, the $S_c - S_{c_3}$ values, that is, the change of concrete strain after stretching, is calculated for each selected level of concrete section. For the loaded member, it also calculates for alternate paths 3*-6* and 3**-6** by calling subroutine ALTPATH. Concrete stresses and strains at the top, centroid, c.g.s. and bottom fibers of concrete gross section are printed out for the loading or unloading path.

Subroutine ALTPATH: Called from subroutine ACTPATH, this subroutine provides the calculations of prestress loss, and stress and strain for concrete and steel for the two alternate paths:
(1) completely unloaded path, 3*-6*, and (2) completely loaded path from the prestressing time, 3**-6**. Except for the $S_c - S_{c_3}$ values which are not calculated in this subroutine, the same types of calculations and print-outs as mentioned in subroutine ACTPATH are given in this subroutine.

5. EXAMPLES

5.1 Problem Description

For the purposes of illustrating the method developed in Chapter 3 and comparing it with several other methods, an example is given in this chapter, with solutions by three different methods: (1) PCI - General Method, (2) Current AASHO Method and (3) the method developed in Chapter 3. Notations having been defined in previous chapters are not redefined here. Any new notation will be defined at its first appearance. The sign convention for concrete stresses is positive for compression and negative for tension, while for steel stresses, it is positive for tension and negative for compression.

The example problem deals with an AASHO type IV I-beam which is used for a bridge spanning 80 ft. center to center. Concrete characteristics are those corresponding to the upper bound potential loss as identified from Lehigh Research Project No. 339. Prestressing is by means of post-tensioning thirty-one 7-wire stress-relieved 1/2 in. diameter strands of the 270 k grade, with a total steel area of 4.74 sq. in. Initial tensioning stress is 189,000 psi at midspan section after allowances for friction and anchorage losses. Six beams are used, at a lateral spacing of 5 ft. center to center. The bridge has a 7-1/2 in. cast-in-place concrete deck (7 in. effective thickness). An additional superimposed dead load of 30 psf (= 150 pℓf) is considered. The properties of the cross section are:

For the precast girder section (see Fig. 5)

$A_g = 789$ sq. in.

$I_g = 260{,}730$ in.^{4}

$e_g = 20.47$ in. at midspan

$= 10.23$ in. at end section

For the composite section, the area, moment of inertia and eccentricity are:

$A_{cs} = 1{,}029$ sq. in.

$I_{cs} = 556{,}789$ in.^{4}

$e_{cs} = 31.85$ in. at midspan

The properties of the materials are:

For concrete (same for beam and slab)

Unit weight of concrete = 145 pcf

i) At post-tensioning time, the compressive strength, elastic modulus and steel-to-concrete modular ratio are:

$f_{ci} = 5{,}000$ psi $\quad E_{ci} = 4.08 \times 10^6$ psi $\quad n_i = 7.1$

ii) At 28 days:

$f'_c = 6{,}000$ psi $\quad E_c = 4.47 \times 10^6$ psi $\quad n = 6.5$

For steel, the yield strength is:

$f_y = 226{,}000$ psi

Stretching of strands is completed in two steps, the first step involves fifteen strands, and the second step sixteen.

The sequence of loading is as follows:

Post-tensioning - 20 days after end of steam curing

Casting of slab - 90 days after post-tensioning

Superimposed dead load - 150 days after post-tensioning

The midspan bending moments caused by the several categories of loads are:

i) Girder load:

$$\text{Weight of girder section} = (145)\left(\frac{789}{144}\right) = 794 \text{ p}\ell\text{f}$$

The moment due to girder weight is:

$$M_G = \frac{(794)\ (80)^2\ (12)}{8} = 7{,}620 \text{ k-in.}$$

ii) Cast-in-place slab:

$$\text{Weight of slab section} = \frac{(145)\ (7.5)\ (5)}{12} = 453 \text{ p}\ell\text{f}$$

The moment due to slab (and diaphragm) weight is:

$$M_s = \frac{(453)\ (80)^2\ (12)}{8} = 4{,}350 \text{ k-in.}$$

iii) Superimposed dead loads:

The moment due to superimposed dead load is:

$$M_D = \frac{(30)\ (5)\ (80)^2\ (12)}{8} = 1{,}440 \text{ k-in.}$$

5.2 Solution by the PCI General Method

Concrete stresses at centroid of steel and steel stresses due to various loads:

i) Girder weight (carried by the girder section)

$$\frac{M_G e_g}{I_g} = - \frac{(7,620)\ (20.47)}{260,730} = - 600 \text{ psi}$$

Steel stress = (7.1) (600) = 4,260 psi

ii) Slab weight (carried by the girder section)

$$\frac{M_s e_g}{I_g} = - \frac{(4,350)\ (20.47)}{260,730} = - 340 \text{ psi}$$

Steel stress = (6.5) (340) = 2,210 psi

iii) Superimposed dead load (carried by composite section):

$$\frac{M_D e_{cs}}{I_{cs}} = - \frac{(1,440)\ (31.85)}{556,789} = -82 \text{ psi}$$

Steel stress = (6.5) (82) = 530 psi

Basic Creep and Shrinkage Values (see Ref. 7)

Creep

For normal weight concrete and steam curing, the ultimate loss of prestress due to creep of concrete is:

UCR = 16.5

The volume to surface ratio of the member is:

$$V/S = \frac{757,440}{159,706} = 4.74$$

The factor that accounts for the effect of size and shape of a member on creep of concrete is:

SCF = 0.7

(UCR) (SCF) = (16.5) (0.7) = 11.6

∴ The loss of prestress due to creep of concrete over time interval t_1 to t is:

$$CR = (11.6)\ (PCR)\ (f_{ct})$$

where: $PCR = (AUC \text{ at } t) - (AUC \text{ at } t_1)$

AUC = Amount of ultimate creep at time after prestressing

t = Time after prestressing at the end of a time interval, in days

t_1 = Time after prestressing at the beginning of a time interval, in days

f_{ct} = Concrete stress at centroid of steel at time t_1, in psi

Shrinkage

The ultimate loss of prestress due to shrinkage of concrete is:

$$USH = 27{,}000 - \frac{3{,}000\ E_c}{10^6} = 13{,}590 \text{ psi}$$

For V/S = 4.74, the factor that accounts for the effect of size and shape of a member on concrete shrinkage is:

SSF = 0.7

(USH) (SSF) = (13,590) (0.7) = 9,510 psi

∴ SH = (9,510) (PSH)

where: $PSH = (AUS \text{ at } t) - (AUS \text{ at } t_1)$

AUS = Amount of ultimate shrinkage at time after end of curing

Time Interval I: From End of Curing of Concrete to Anchorage

No loss during this period for post-tensioned members.

Time Interval II: From Anchorage to Casting of Slab

(a) Immediate Loss:

i) At the middle section

Stage 1: Tensioning of fifteen strands resisted by the net concrete section:

$A_n = 784.3$ sq. in.

$e_n = 20.6$ in.

$I_n = 258{,}732$ in.^{4}

$$f_{c_3} = N_s a_{ps} f_{s_2} \left(\frac{1}{A_n} + \frac{e_n^2}{I_n} \right)$$

$$= (15)\ (0.153)\ (189{,}000) \left(\frac{1}{784.3} + \frac{20.6^2}{258{,}732} \right)$$

$$= 1{,}264 \text{ psi}$$

Stage 2: Tensioning of sixteen strands resisted by the net concrete section combined with the fifteen strands already anchored.

$$A_t = 800.6 \text{ sq. in.}$$

$$e_t = 20.1 \text{ in.}$$

$$I_t = 266{,}512 \text{ in.}^4$$

$$f_{c_3} = N_s a_{ps} f_{s_2}\left(\frac{1}{A_t} + \frac{e_t^2}{I_t}\right)$$

$$= (16)\ (0.153)\ (189{,}000)\left(\frac{1}{800.6} + \frac{20.1^2}{266{,}512}\right)$$

$$= 1{,}280 \text{ psi}$$

∴ The total concrete prestress at c.g.s. immediately after post-tensioning is:

$$f_{c_3} = 1{,}264 + 1{,}280 = 2{,}544 \text{ psi}$$

ii) <u>At the end section</u>: Similar to the midspan section

Stage 1: $A_n = 784.3$ sq. in.

$e_n = 10.3$ in.

$I_n = 260{,}231$ in.^{4}

$$f_{c_3} = N_s a_{ps} f_{s_2}\left(\frac{1}{A_n} + \frac{e_n^2}{I_n}\right)$$

$$= (15)\ (0.153)\ (189{,}000)\left(\frac{1}{784.3} + \frac{10.3^2}{260{,}231}\right)$$

$$= 730 \text{ psi}$$

Stage 2: $A_t = 800.6$ sq. in.

$e_t = 10.0$ in.

$I_t = 262{,}175$ in.^{4}

$$f_{c_3} = (16)\ (0.153)\ (189{,}000)\left(\frac{1}{800.6} + \frac{10^2}{262{,}175}\right)$$

$$= 756 \text{ psi}$$

$\therefore$ The total concrete prestress at c.g.s. immediately after post-tensioning is:

$$f_{c_3} = 730 + 756 = 1{,}486 \text{ psi}$$

Assuming a parabolic variation of f_{c_3}, the average of f_{c_3} along the length of member is:

$$f_{c_3avg} = \frac{2}{3}\ (2{,}544 - 1{,}486) + 1{,}486 = 2{,}190 \text{ psi}$$

Assuming a factor of one-half for the estimation of elastic shortening loss, $\alpha = \frac{1}{2}$

$$\therefore \text{ES} = \alpha n_i f_{c_3avg} = \frac{1}{2}\ (7.1)\ (2{,}190) = 7{,}775 \text{ psi}$$

The streel stress immediately after Prestressing (without the effect of girder weight) is:

$$f_{s_3} = f_{s_2} - \text{ES} = 189{,}000 - 7{,}775 = 181{,}200 \text{ psi}$$

$\therefore$ Immediately after the prestresses (not including the stresses caused by M_G) are:

$$f_{s_3} = 181{,}200 \text{ psi}$$

$$f_{c_3} = 2{,}190 \text{ psi}$$

Initial prestress loss = 7,775 psi = 4.1% of fsi

(b) Time-Dependent Loss:

Immediately after prestressing, the material stresses at c.g.s., including the stresses caused by M_G, are:

f_{st} = Total steel stress at time t_1

$= 181{,}200 + 4{,}260 = 185{,}500$ psi

$f_{ct} = 2{,}190 - 600 = 1{,}590$ psi

For creep, $t_1 = 0$ $\quad t = 90$ days

$PCR = 0.51 - 0 = 0.51$

$CR = (11.6)\ (0.51)\ (1{,}590) = 9{,}406$ psi

For shrinkage, $t_1 = 20$ days $\quad t = 110$ days

$PSH = 0.63 - 0.36 = 0.27$

$SH = (9{,}510)\ (0.27) = 2{,}570$ psi

For relaxation, $t_1 = 1/24$ days (see Ref. 7) $\quad t = 90$ days

$t/t_1 = 2{,}160$

$f_{st}/f_y = 185.5/226 = 0.82$

The loss of prestress due to steel relaxation over time interval t_1 to t is:

$$RET = (185{,}500)\left(\frac{\log 2{,}160}{10}\right)(0.82 - 0.55)$$

$$= 16{,}700 \text{ psi}$$

Total loss in time Interval II

$$= ES + CR + SH + RET$$

$$= 7{,}775 + 9{,}406 + 2{,}570 + 16{,}700$$

$$= 36{,}451 \text{ psi}$$

∴ At the end of interval II

The steel stress due to prestress alone after post-tensioning is:

$$f_{sp} = 189{,}000 - 36{,}451 = 152{,}549 \text{ psi}$$

The concrete stress at centroid of steel due to prestress alone after post-tensioning is:

$$f_{cp} = 2{,}190 \times \frac{152{,}549}{181{,}200} = 1{,}840 \text{ psi}$$

Time Interval III: From Casting of Slab to Application of Superimposed Dead Load

Immediately after casting of slab, the material stresses at c.g.s., including the stresses caused by M_G and M_S, are:

$$f_{st} = 152{,}549 + 4{,}260 + 2{,}210 = 159{,}019 \text{ psi}$$

$$f_{ct} = 1{,}840 - 600 - 340 = 900 \text{ psi}$$

For creep, $t_1 = 90$ days $\quad t = 150$ days

$$PCR = 0.58 - 0.51 = 0.07$$

$$CR = (11.6)\ (0.07)\ (900) = 731 \text{ psi}$$

For shrinkage, t_1 = 110 days   t = 170 days

$$PSH = 0.67 - 0.63 = 0.04$$

$$SH = (9,510)\ (0.04) = 380 \text{ psi}$$

For relaxation, t_1 = 90 days   t = 150 days $t/t_1 = 1.67$

$$f_{st}/f_y = 159/226 = 0.70$$

$$RET = (159,019) \left(\frac{\log 1.67}{10}\right) (0.70 - 0.55)$$

$$= 531 \text{ psi}$$

Total loss in time interval III

$$= CR + SH + RET$$

$$= 731 + 380 + 531$$

$$= 1,642 \text{ psi}$$

∴ At the end of interval III

$$f_{sp} = 152,549 - 1,642 = 150,907 \text{ psi}$$

$$f_{cp} = 2,190 \times \frac{150,907}{181,200} = 1,824 \text{ psi}$$

Time Interval IV: From Application of Superimposed Dead Load to End of One Year.

Immediately after the application of superimposed dead loads, the material stresses at c.g.s., including the stresses caused by M_G, M_S and M_D, are:

$$f_{st} = 150,907 + 4,260 + 2,210 + 530 = 157,907 \text{ psi}$$

$$f_{ct} = 1,824 - 600 - 340 - 82 = 802 \text{ psi}$$

For creep, $t_1 = 150$ days $t = 365$ days

$$PCR = 0.74 - 0.58 = 0.16$$

$$CR = (11.6)\ (0.16)\ (802) = 1,490 \text{ psi}$$

For shrinkage, $t_1 = 170$ days $t = 385$ days

$$PSH = 0.86 - 0.67 = 0.19$$

$$SH = (9,510)\ (0.19) = 1,807 \text{ psi}$$

For relexation, $t_1 = 150$ days $t = 365$ days $t/t_1 = 2.43$

$$f_{st}/f_y = 157.9/226 = 0.7$$

$$RET = (157,907)\left(\frac{\log 2.43}{10}\right)(0.7 - 0.55)$$

$$= 913 \text{ psi}$$

Total loss in time interval IV

$$= CR + SH + RET$$

$$= 1,490 + 1,807 + 913 = 4,210 \text{ psi}$$

∴ At the end of interval IV

$$f_{sp} = 150,907 - 4,210 = 146,697 \text{ psi}$$

$$f_{cp} = 2,190 \times \frac{146,697}{181,200} = 1,773 \text{ psi}$$

Time Interval V: From End of One Year to End of Service Life, Taken as One Hundred Years.

Immediately after end of one year, the material stresses at c.g.s., including the stresses caused by M_G, M_S and M_D, are:

$$f_{st} = 146,697 + 4,260 + 2,210 + 530 = 153,697 \text{ psi}$$

$$f_{ct} = 1,773 - 600 - 340 - 82 = 751 \text{ psi}$$

For creep, $t_1 = 365$ days

$$PCR = 1.00 - 0.74 = 0.26$$

$$CR = (11.6)(0.26)(751) = 2,265 \text{ psi}$$

For shrinkage, $t_1 = 385$ days

$$PSH = 1.00 - 0.86 = 0.14$$

$$SH = (9,510)(0.14) = 1,330 \text{ psi}$$

For relexation, $t_1 = 365$ days $t = 36,500$ days $t/t_1 = 100$

$$f_{st}/f_y = 153.7/226 = 0.68$$

$$RET = (153,697)\left(\frac{\log 100}{10}\right)(0.68 - 0.55)$$

$$= 3,996 \text{ psi}$$

Total loss in time interval V

$$= CR + SH + RET$$

$$= 2,265 + 1,330 + 3,996$$

$$= 7,591 \text{ psi}$$

$\therefore$ At the end of time interval V

$$f_{sp} = 146,697 - 7,591 = 139,106 \text{ psi}$$

$$f_{cp} = 2,190 \times \frac{139,106}{181,200} = 1,681 \text{ psi}$$

Summary

Time Interval	SH	CR	RET
I	0	0	0
II	2,570	9,406	16,700
III	380	731	531
IV	1,807	1,490	913
V	1,330	2,265	3,996
Σ	6,087	13,892	22,140

$$\Delta f_s = ES + \overset{N}{\Sigma} (SH + CR + RET)$$

$$= 7,775 + 6,087 + 13,892 + 22,140$$

$$= 49,894 \text{ psi}$$

$$= 26.4\% \text{ of } f_{si}$$

5.3 Current AASHO Method

Concrete stresses at centroid of steel:

i) Initial prestress (carried by the girder section)

a) At the middle section

$$(f_{si})\ (A_{ps})\left(\frac{1}{A_g} + \frac{e_g^2}{I_g}\right)$$

$$= (189{,}000)\ (4.74)\left(\frac{1}{789} + \frac{20.47^2}{260{,}730}\right) = 2{,}575 \text{ psi}$$

b) At the end section

$$(f_{si})\ (A_{ps})\left(\frac{1}{A_g} + \frac{e_g^2}{I_g}\right)$$

$$= (189{,}000)\ (4.74)\left(\frac{1}{789} + \frac{10.23^2}{260{,}730}\right) = 1{,}495 \text{ psi}$$

ii) Girder load (carried by the girder section)

At midspan $\frac{M_G e_g}{I_g} = -600$ psi

At supports $\frac{M_G e_g}{I_g} = 0$

iii) Cast-in-place slab load (carried by the girder section) and superimposed dead load (carried by the composite section)

At midspan $\frac{M_S e_g}{I_g} + \frac{M_D e_{cs}}{I_{cs}} = -340 - 82 = -422$ psi

At supports $\frac{M_S e_g}{I_g} + \frac{M_D e_{cs}}{I_{cs}} = 0$

Elastic shortening

At midspan $f_{cr} = 2{,}575 - 600 = 1{,}975$ psi

At supports $f_{cr} = 1{,}495 - 0 = 1{,}495$ psi

Average $f_{cr} = \frac{1}{2}(1{,}975 + 1{,}495) = 1{,}725$ psi

$ES = 7f_{cr} = (7)(1{,}725) = 12{,}075$ psi

Initial prestress loss = 12,075 psi = 6.4% of f_{si}

Shrinkage loss

In the state of Pennsylvania

relative humidity = 70 - 75%

$\therefore SH = 10{,}000$ psi

Creep loss

At midspan $f_{cd} = 2{,}575 - 600 - 422 = 1{,}553$ psi

At supports $f_{cd} = 1{,}495 - 0 - 0 = 1{,}495$ psi

Average $f_{cd} = \frac{1}{2}(1{,}553 + 1{,}495) = 1{,}524$ psi

$CR_c = 16\ f_{cd} = 16\ (1{,}524) = 24{,}384$ psi

Relaxation loss

$$
\begin{aligned}
CR_{sp} &= 20{,}000 - 0.125\ [0.8\ (SH) + 0.5\ (ES) + CR_c] \\
&= 20{,}000 - 0.125\ [0.8\ (10{,}000) + 0.5\ (12{,}075) + 24{,}384] \\
&= 15{,}197 \text{ psi}
\end{aligned}
$$

Total prestress loss

$$
\begin{aligned}
\Delta f_s &= 0.8\ (SH) + 0.5\ (ES) + CR_c + CR_{sp} \\
&= 0.8\ (10{,}000) + 0.5\ (12{,}075) + 24{,}384 + 15{,}197 \\
&= 53{,}619 \text{ psi} \\
&= 28.4\% \text{ of } f_{si}
\end{aligned}
$$

5.4 New Method

Coefficients for Concrete and Steel Surfaces (Tables 1 and 2)

i) 1/2 in. diameter stress-relieved strand

The coefficients of instantaneous stress-strain relationship of steel are:

$A_1 = -0.04229$

$A_2 = 1.21952$

$A_3 = -0.17827$

Assuming strands are supplied by manufacturer C, the relaxation coefficients are:

$B_1 = -0.07880$

$B_2 = -0.00762$

$B_3 = 0.14598$

$B_4 = 0.05920$

ii) Upper-bound-loss concrete

$C_1 = 0.02500$

$D_1 = -0.00668$

$D_2 = 0.02454$

$E_1 = -0.01280$

$E_2 = 0.00675$

$E_3 = -0.00060$

$E_4 = 0.01609$

Step 1

Evaluation of k_2, k_3, β and $f'_{c\ell}$ (see Chapter 3)

$f_{s_2} = 189$ ksi $\quad f_{pu} = 270$ ksi $\quad f_{s_2}/f_{pu} = 189/270 = 0.7$

$$f_{s_2} = f_{pu}\ (A_1 + A_2 S_{s_2} + A_3 S_{s_2}^{\,2})$$

$$\therefore S_{s_2} = k_2 = \frac{-A_2 + \sqrt{A_2^2 - 4A_3\ (A_1 - f_{s_2}/f_{pu})}}{2A_3}$$

$$= \frac{-(1.21952) + \sqrt{(1.21952)^2 - 4\ (-0.17827)\cdot(-0.04229 - 0.7)}}{2\ (-0.17827)}$$

$= 0.675$ in./in.

$k_3 = 20$ days

$$\beta = \frac{A_g I_g}{A_{ps}\ (I_g + A_g e_g^2)} = \frac{(789)\ (260{,}730)}{4.74\ [260{,}730 + (789)\ (20.47)^2]} = 73.4$$

$f'_{c\ell} = 0.600 + 0.340 + 0.082 = 1.022$ ksi

(for the sign convention of $f'_{c\ell}$, see Section 3.1, p. 17)

Step 2

Calculations of f_{c_3} and k_4

At the midspan section, $f_{c_3} = 2.544$ ksi (see Section 5.2, p. 41)

$$k_4 = D_1 + D_2 \log\ (k_3 + 1) + k_2 + (1 - \alpha)\ C_1 f_{c_3}$$

$$= -0.00668 + 0.02454 \log\ (20 + 1) + 0.675$$

$$+ (1 - 0.5)\ (0.025)\ (2.544)$$

$= 0.733$

Step 3

Calculations of parameters

$$P_1 = A_1 f_{pu}$$

$$= (-0.04229)\ (270)$$

$$= -11.42$$

$$P_2 = [A_2 - B_1 - B_2 \log (t_s + 1)]\ f_{pu}$$

$$= [1.21952 - (-0.07880) - (-0.00762) \log (t_s + 1)]\ (270)$$

$$= 350.5 + 2.06 \log (t_s + 1)$$

$$P_3 = [A_3 - B_3 - B_4 \log (t_s + 1)]\ f_{pu}$$

$$= [(-0.17827) - 0.14598 - 0.05920 \log (t_s + 1)]\ (270)$$

$$= -87.5 - 15.98 \log (t_s + 1)$$

$$Q_1 = D_1 + E_1 + D_2 \log (t_c + 1) + E_2 \log (t_s + 1)$$

$$= -0.00668 - 0.01280 + 0.02454 \log (t_c + 1) + 0.00675 \log (t_s + 1)$$

$$= -0.01948 + 0.02454 \log (t_c + 1) + 0.00675 \log (t_s + 1)$$

$$Q_2 = C_1 + E_3 + E_4 \log (t_s + 1)$$

$$= 0.02500 - 0.00060 + 0.01609 \log (t_s + 1)$$

$$= 0.02440 + 0.01609 \log (t_s + 1)$$

In the following, calculations for the time immediately after application of loading are demonstrated. For the sake of simplicity, the superimposed dead load of 30 psf is treated as if acting at the time when the slab is cast. The error will be very small and on the over-estimation side. At the time of deck slab casting,

t_s = 90 days and t_c = 110 days

$$\therefore P_2 = 350.5 + 2.06 \log (90 + 1)$$

$$= 354.54$$

$$P_3 = -87.5 - 15.98 \log (90 + 1)$$

$$= -118.8$$

$$Q_1 = -0.01948 + 0.02454 \log (110 + 1) + 0.00675 \log (90 + 1)$$

$$= 0.04392$$

$$Q_2 = 0.02440 + 0.01609 \log (90 + 1)$$

$$= 0.05590$$

$$k_4 - Q_1 = 0.73300 - 0.04392 = 0.6891$$

$$R_1 = P_1 + P_2 (k_4 - Q_1) + P_3 (k_4 - Q_1)^2$$

$$= -11.42 + 354.54 (0.6891) + (-118.8) (0.6891)^2$$

$$= 176.48$$

$$R_2 = -Q_2 [P_2 + 2P_3 (k_4 - Q_1)]$$

$$= -0.0559 [354.54 + 2 (-118.8) (0.6891)]$$

$$= -10.67$$

$$R_3 = P_3 Q_2^2$$

$$= (-118.8) (0.0559)^2$$

$$= -0.371$$

Step 4

Calculation of concrete stress at c.g.s.

$$(R_1 - \beta f'_{c\ell}) + (R_2 - \beta + 1)\ f_{cs} + R_3 f^2_{cs} = 0$$

$$R_1 - \beta f'_{c\ell} = 176.48 - (73.4)\ (1.022)$$

$$= 101.47$$

$$R_2 - \beta + 1 = -10.67 - 73.4 + 1$$

$$= -83.07$$

$$-0.371\ f^2_{cs} - 83.07\ f_{cs} + 101.47 = 0$$

$$f_{cs} = \frac{-(-83.07) - \sqrt{(-83.07)^2 - 4\ (-0.371)\ (101.47)}}{2\ (-0.371)}$$

$$= 1.213 \text{ ksi}$$

Step 5

Calculation of steel stress

$$f_s = (\beta - 1)\ f_{cs} + \beta f'_{c\ell}$$

$$= (73.4 - 1)\ (1.213) + 73.4\ (1.022)$$

$$= 162.83 \text{ ksi}$$

Step 6

Calculations of concrete and steel strains

$$S_c = Q_1 + Q_2 f_{cs}$$

$$= 0.04392 + 0.0559\ (1.213)$$

$$= 0.1117 \text{ in./in.}$$

$S_s = k_4 - S_c$

$= 0.7330 - 0.1117$

$= 0.6213$ in./in.

Total prestress loss immediately after application of load

$= 189 - (162.83 - 4.26 - 2.21 - 0.53)$

$= 33.17$

$= 17.6\%$ of f_{si}

Stress and strain conditions at other times are calculated by the same procedure (Steps 3 to 6). The results are as follows:

Immediately after post-tensioning

$t_s = 0$ $t_c = 20$ days $f'_{c\ell} = 0$

$f_{cs} = 2.492$ ksi

$S_c = 0.0881$ in./in.

$f_s = 180.40$ ksi

$S_s = 0.6449$ in./in.

Initial prestress loss

$= 189 - 180.4$

$= 8.6$ ksi

$= 4.6\%$ of f_{si}

Immediately before application of loads

t_s = 90 days t_c = 110 days $f'_{c\ell}$ = 0.600 ksi

f_{cs} = 1.583 ksi

S_c = 0.1324 in./in.

f_s = 158.65 ksi

S_s = 0.6006 in./in.

Total prestress loss immediately before application of loads:

= 189 - (158.65 - 4.26)

= 34.61 ksi

= 18.3% of f_{si}

At the end of one year

t_s = 365 days t_c = 385 days $f'_{c\ell}$ = 1.022 ksi

f_{cs} = 1.116 ksi

S_c = 0.1335 in./in.

f_s = 155.81 ksi

S_s = 0.5995 in./in.

Total prestress loss at the end of one year

= 189 - (155.8 - 4.26 - 2.21 - 0.53)

= 40.2 ksi

= 21.3% of f_{si}

At the end of the service life, taken as one hundred years

t_s = 36,500 days t_c = 36,520 days $f'_{c\ell}$ = 1.022 ksi

f_{cs} = 0.8187 ksi

S_c = 0.2027 in./in.

f_s = 134.28 ksi

S_s = 0.5303 in./in.

Total prestress loss in one hundred years

$= 189 - (134.28 - 4.26 - 2.21 - 0.53)$

$= 61.72$ ksi

$= 32.7\%$ of f_{si}

The same example was also solved by the computer program PRELOSS. Stress conditions at many more time locations were obtained. The hand calculated results given above agreed with the computer output up to three decimal places.

5.5 Comparison

Among the three different methods, the current AASHO method predicts the higher initial prestress loss than the new method while that predicted by the new method is higher than the PCI - General Method. It should be pointed out that the AASHO method does not explicitly provide an estimate of the initial prestress loss and the elastic loss value is used here for the purpose of comparison. As for the total prestress loss, the new method gives the higher value than the other two methods. In the current AASHO method, the influences of the shrinkage, elastic shortening and creep losses on relaxation are considered, but not vice versa (see Section 1.3). Both the PCI - General Method and the new method considered fully the interference of the several components. The total prestress loss predicted by the PCI - General Method is lower than that predicted by the new method. This is consistent with the comparison between the two methods for pretensioned members. It was known that the concrete characteristics exert a substantial effect on prestress losses and for pretensioned members, the total prestress loss predicted by the PCI - General Method is close to the lower bound predictions[3], therefore it is believed that the same result for post-tensioned members could be expected. In addition, the PCI - General Method does not specify the lifetime of a member, and it is believed that a service life shorter than 100 years was implied.

The current AASHO method gives only the final prestress loss at the end of the service life of the member, while for both the PCI - General Method and the new method, the prestress loss at any arbitrary time can be predicted. The calculations needed for the new method are shorter and simpler than those required for the PCI - General Method. In addition, the PCI - General Method follows a step-by-step procedure, while the new method enables a direct calculation of prestress loss at any time. The steel prestress vs. time curves are plotted for the results obtained by using the current AASHO method, the PCI - General Method and the new method and are shown in Fig. 6. It can be seen that the results obtained by using both the PCI - General Method and the new method agreed very well with each other up to approximately three or four years and the prestress loss predicted in 100 years by the new method is higher.

6. CONCLUSIONS

Based on the development and example problem given in the previous chapters, the following conclusions can be made:

1. The basic principles and procedures developed previously for pretensioned members can be modified for post-tensioned members by appropriate changes in the time and strain relationships.

2. The computer progam PRELOC can be expanded to include both pre- and post-tensioned members.

3. Among the three methods tested in Chapter 5, the current AASHO method predicts the highest initial prestress loss, while the new method predicts the highest total prestress loss at the end of service life of the member.

4. In comparison with the current AASHO method and the PCI - General Method, the new method provides reasonable results throughout the service life of the member. As for the amount of calculations, it requires less calculation effort than the PCI - General Method. In addition, this method provides a direct calculation of prestress loss at any time.

5. Further improvements in the prediction of the prestress losses for post-tensioned members can be made in the following areas:

a. The inclusion of the frictional and anchorage losses estimations in the basic procedures of the prediction of the prestress losses.

b. The establishment of a direct relationship of the concrete prestress at c.g.s., f_{c_3}, in terms of the initial steel stress, thus avoiding the successive calculations used in this thesis.

c. The refinement of stress and strain conditions immediately after post-tensioning for a more precise strain linking relationship as compared to Eq. 3-20.

7. TABLES

TABLE 1: COEFFICIENTS FOR STEEL SURFACES

Instantaneous Stress-Strain Relationship					
All Sizes	All Manufacturers	$A_1 = -0.04229$, $A_2 = 1.21952$, $A_3 = -0.17827$			
Relaxation Coefficients					
Size	Manufacturer	B_1	B_2	B_3	B_4
7/16 in.	B	-0.05243	0.00113	0.11502	0.05228
	C	-0.04697	-0.01173	0.10015	0.05943
	U	-0.06036	0.00891	0.12068	0.02660
	All	-0.05321	0.00291	0.11294	0.03763
1/2 in.	B	-0.06380	0.00359	0.12037	0.05673
	C	-0.07880	-0.00762	0.14598	0.05920
	U	-0.06922	0.00844	0.13645	0.04394
	All	-0.07346	0.00620	0.13847	0.04608
All	All	-0.05867	0.00023	0.11860	0.04858

TABLE 2: COEFFICIENTS FOR CONCRETE SURFACES

Coefficients		Plant AB Upper Bound	Plant CD Lower Bound	Combined
Elastic Strain C_1*		0.02500	0.02105	0.02299
Shrinkage	D_1	-0.00668	-0.00066	-0.00289
	D_2	0.02454	0.01500	0.02031
	D_3	0.00439	-0.00016	0.00128
	D_4	-0.00474	-0.00334	-0.00432
Creep	E_1	-0.01280	-0.00664	-0.01592
	E_2	0.00675	-0.00331	0.00649
	E_3	-0.00060	-0.00371	0.00256
	E_4	0.01609	0.01409	0.01153

* Note: $C_1 = 100/E_c$ where E_c is modulus of elasticity for concrete, in ksi

8. FIGURES

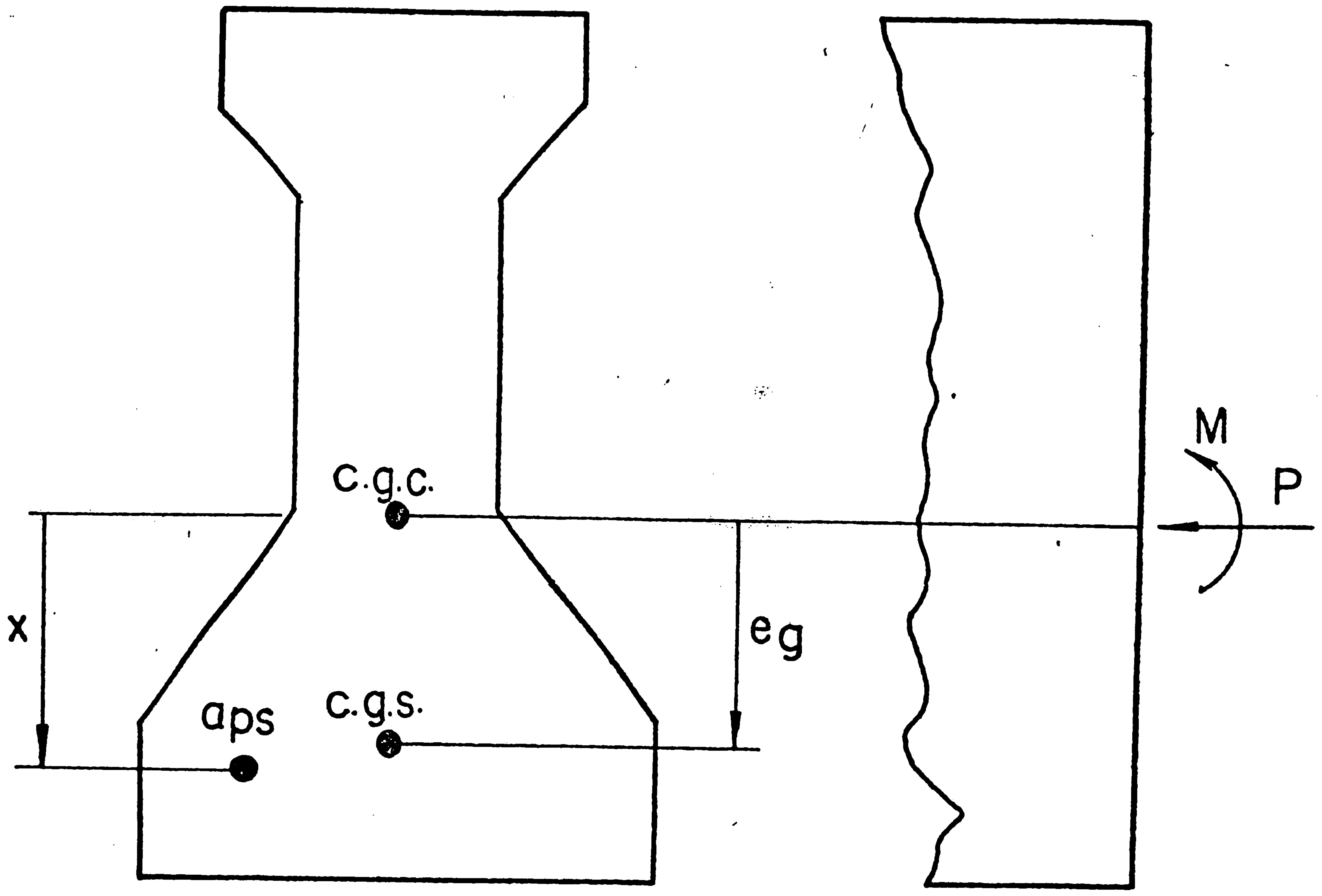


Fig. 1 Applied Axial Load and Applied Bending Moment Acting on the Concrete Cross Section

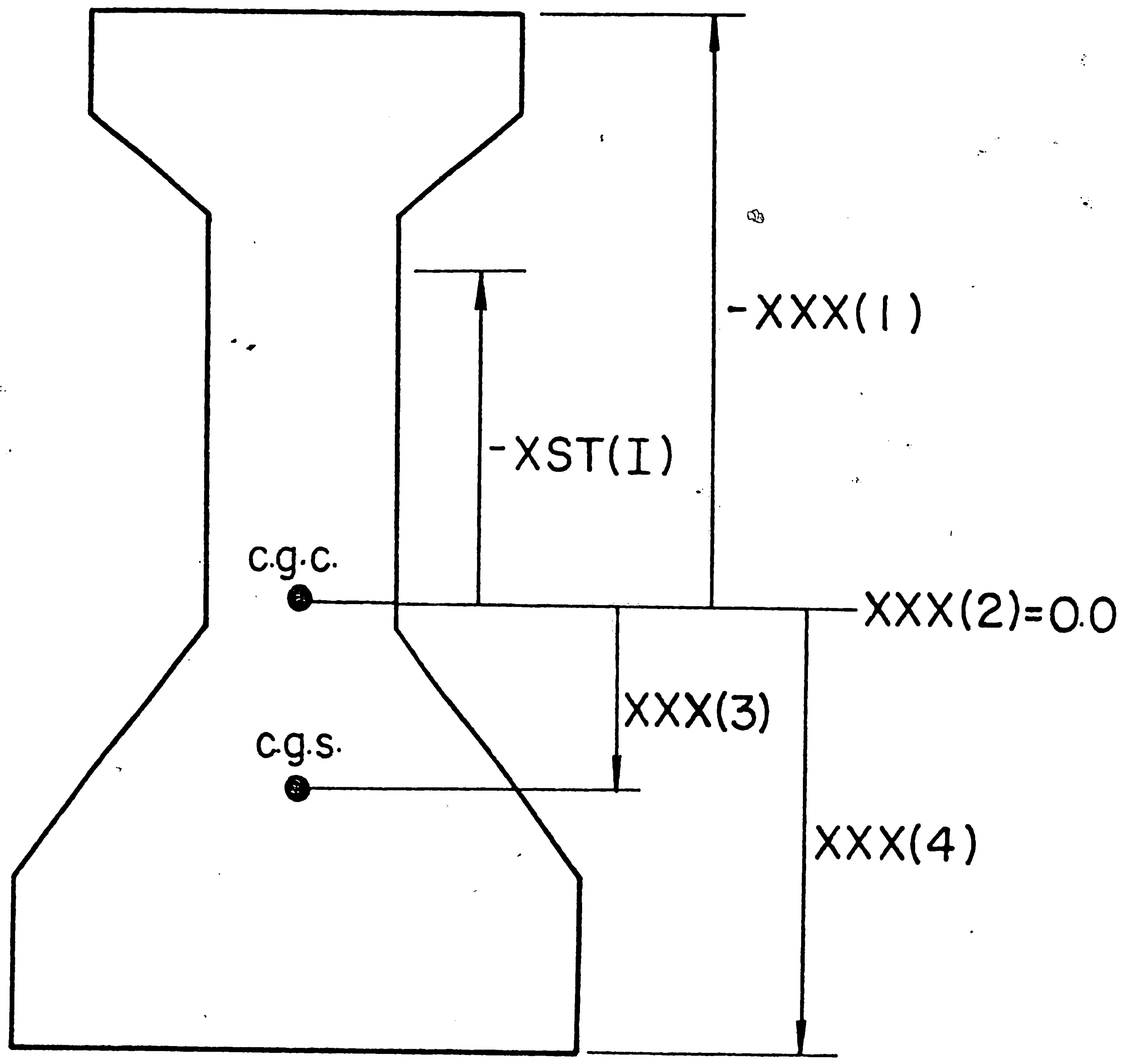


Fig. 2 Distances to Selected Levels with Reference from the Centroid of Concrete Gross Section

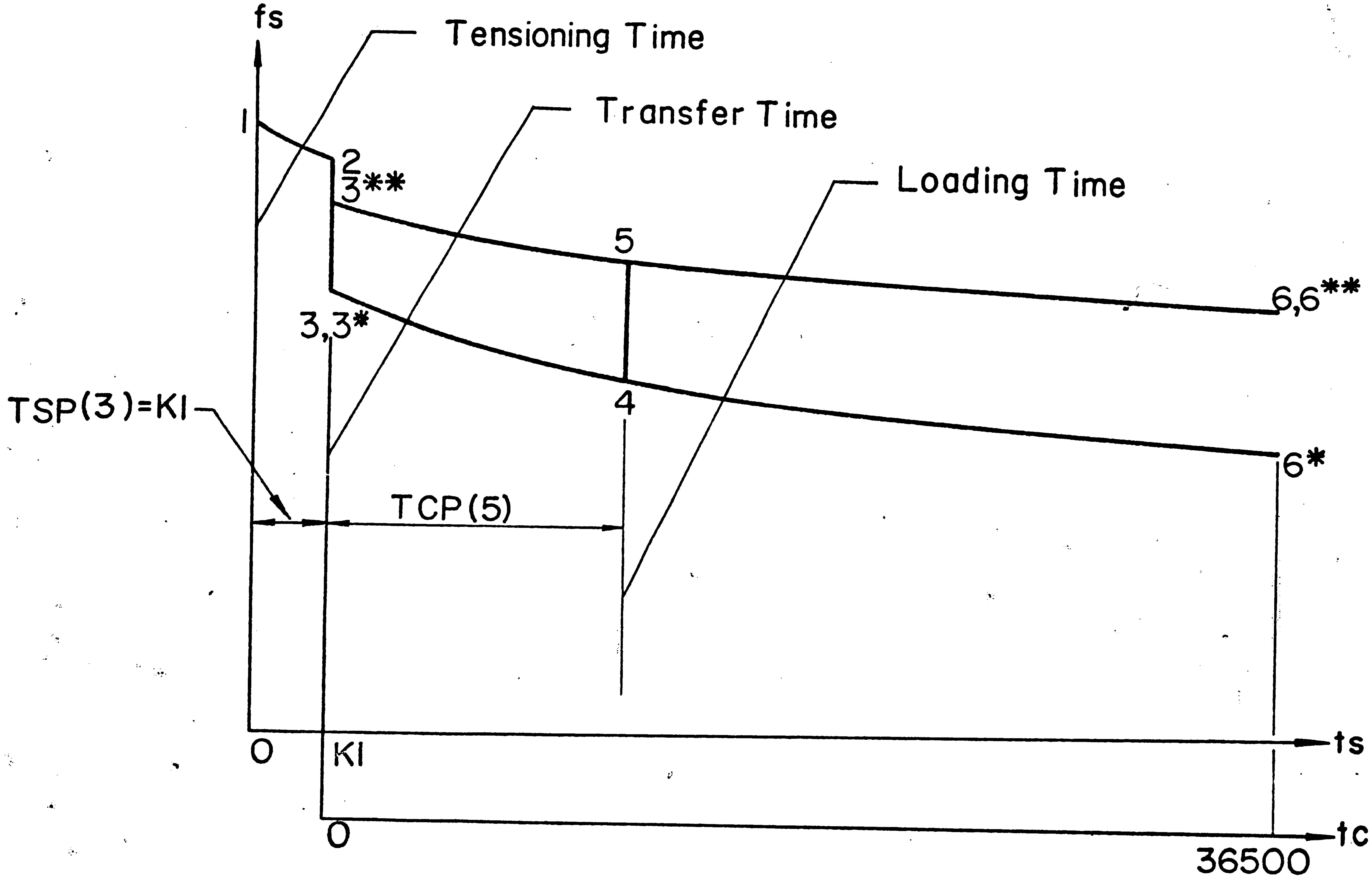


Fig. 3 Typical Variation of Steel Stress with Time for Pretensioned Members

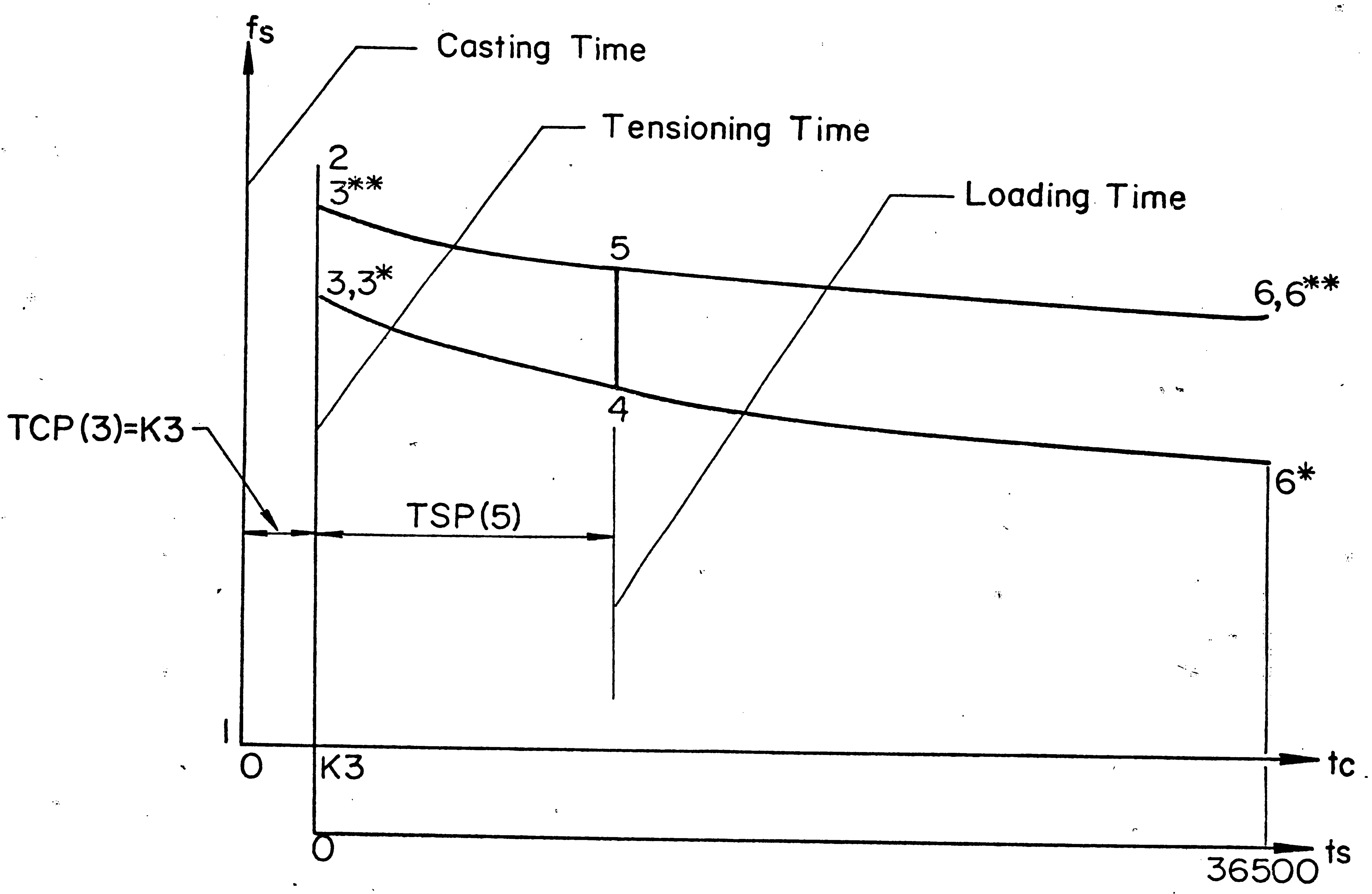
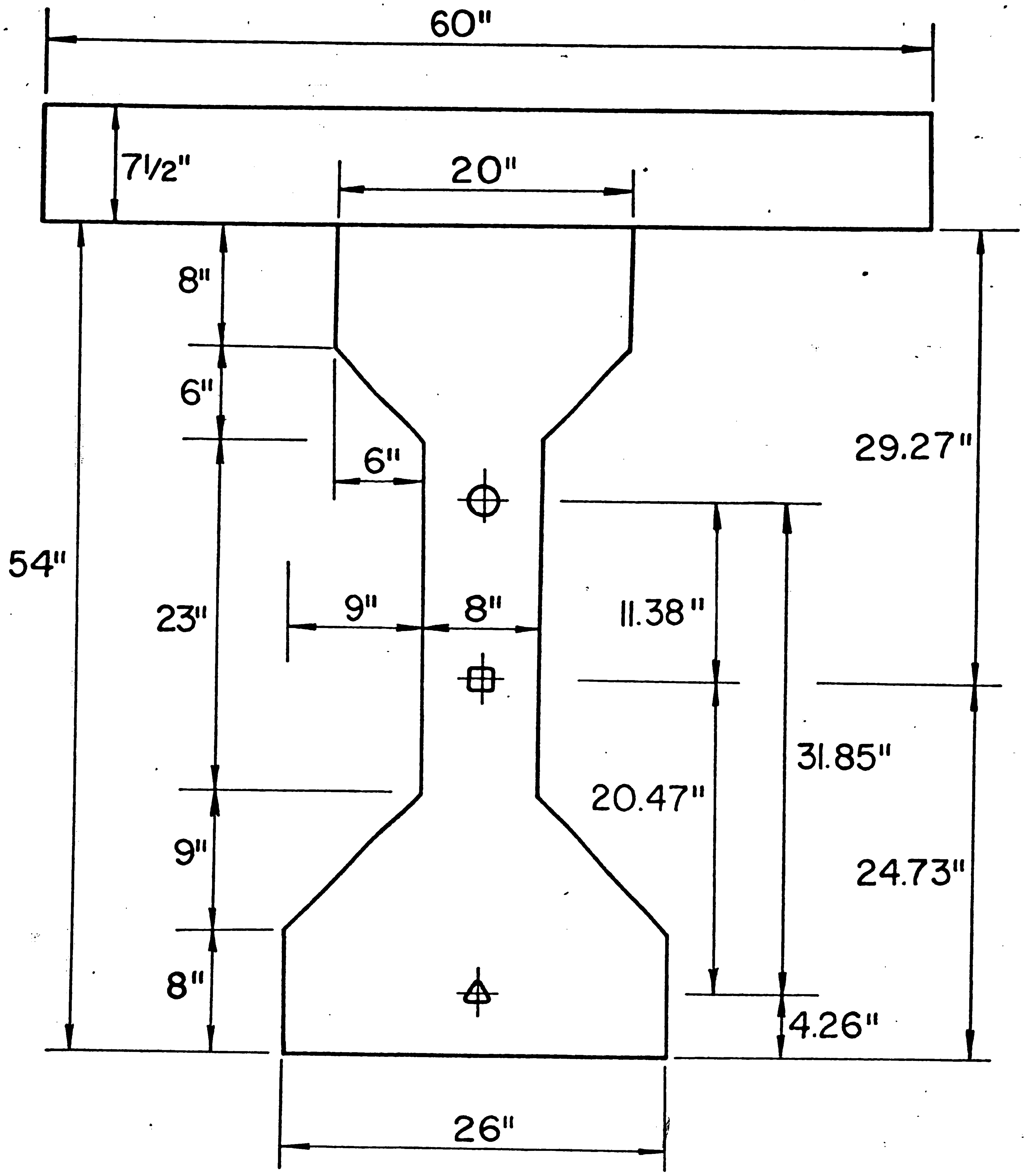


Fig. 4 Typical Variation of Steel Stress with Time for Post-Tensioned Members



△ Centroid of Steel

○ Centroid of Composite Section

□ Centroid of Girder Section

Fig. 5 AASHO Type IV I-Beam Cross Section at Midspan for Example Problem

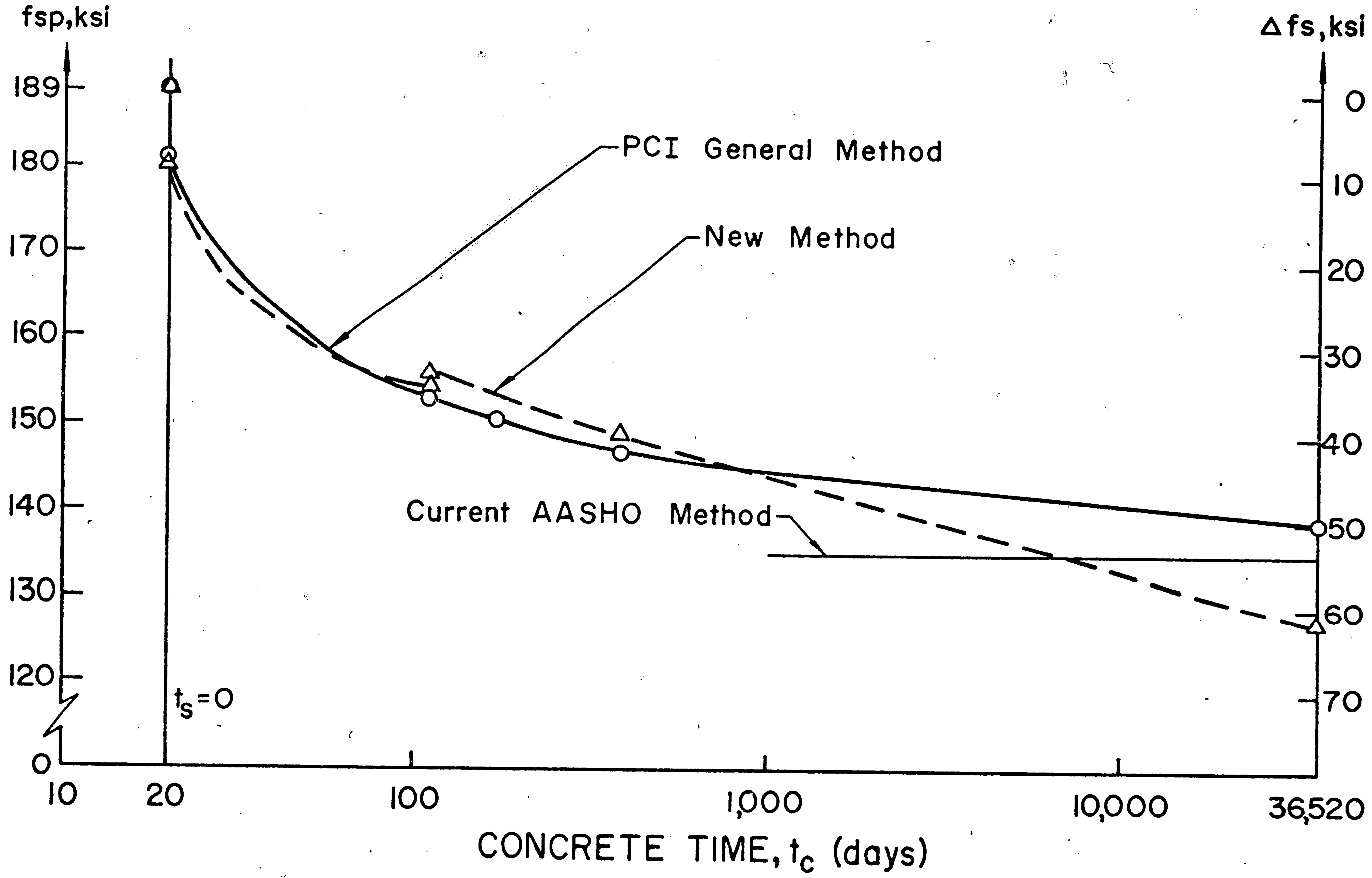
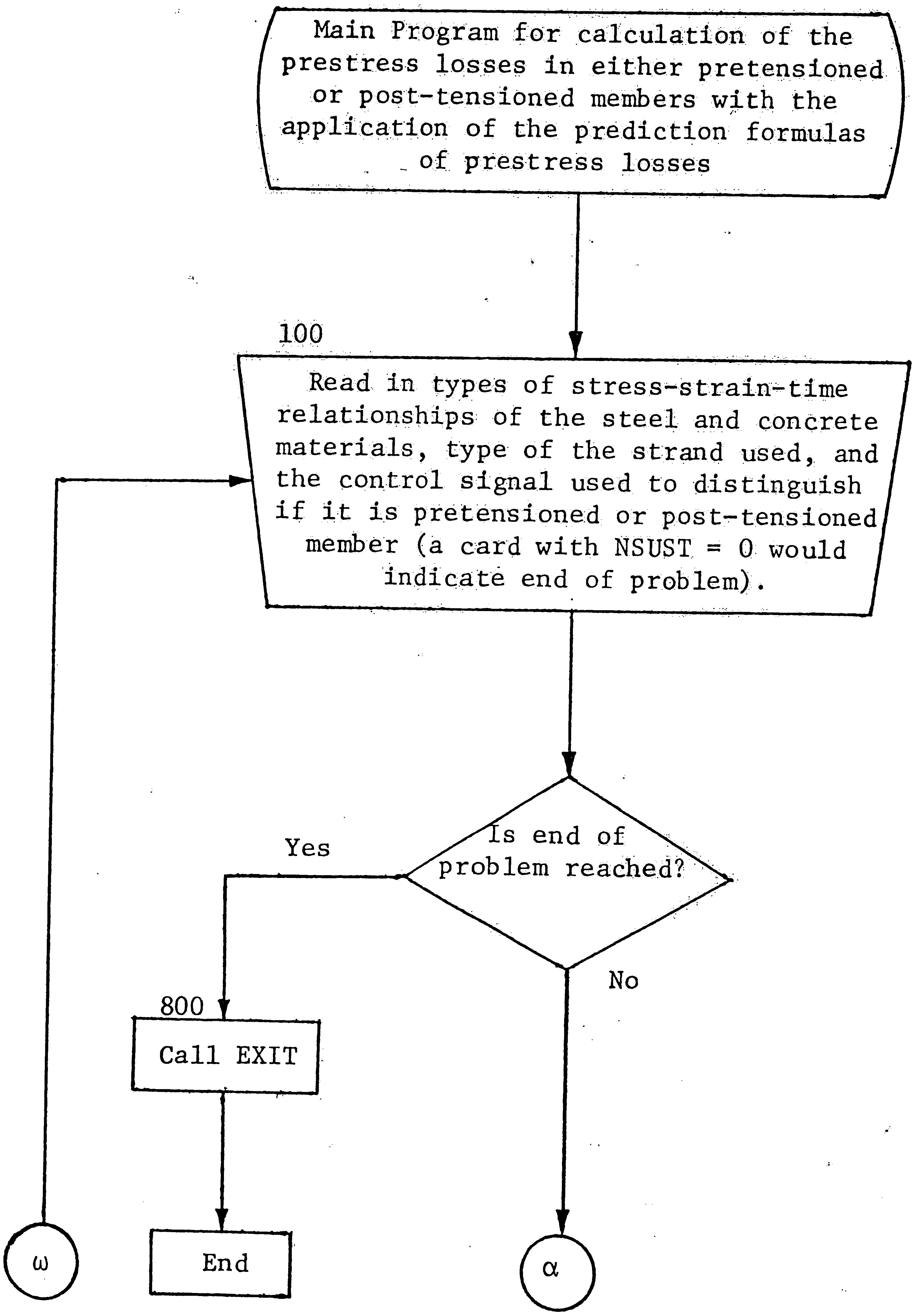


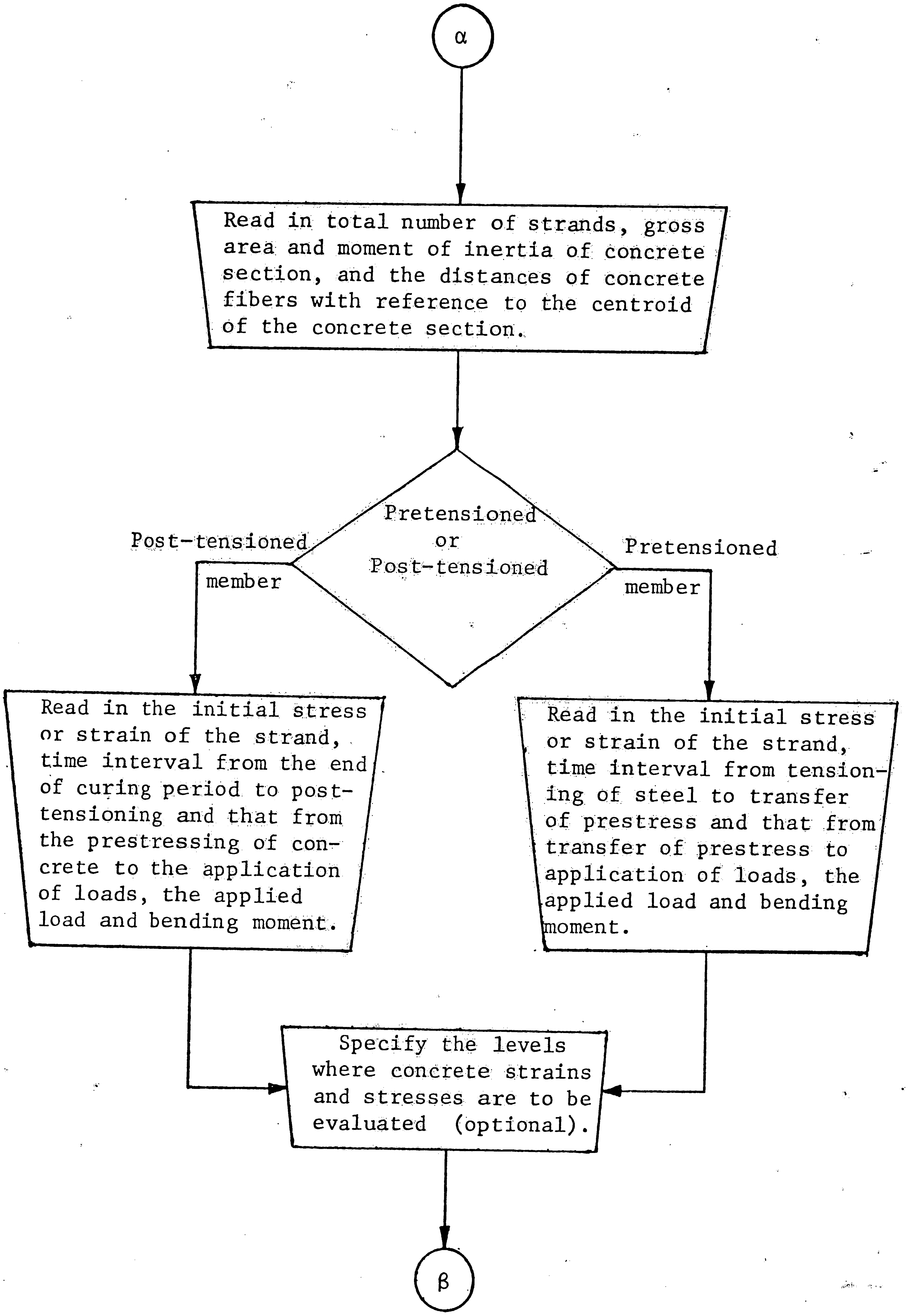
Fig. 6 Variation of Steel Prestress with Time - Example Problem

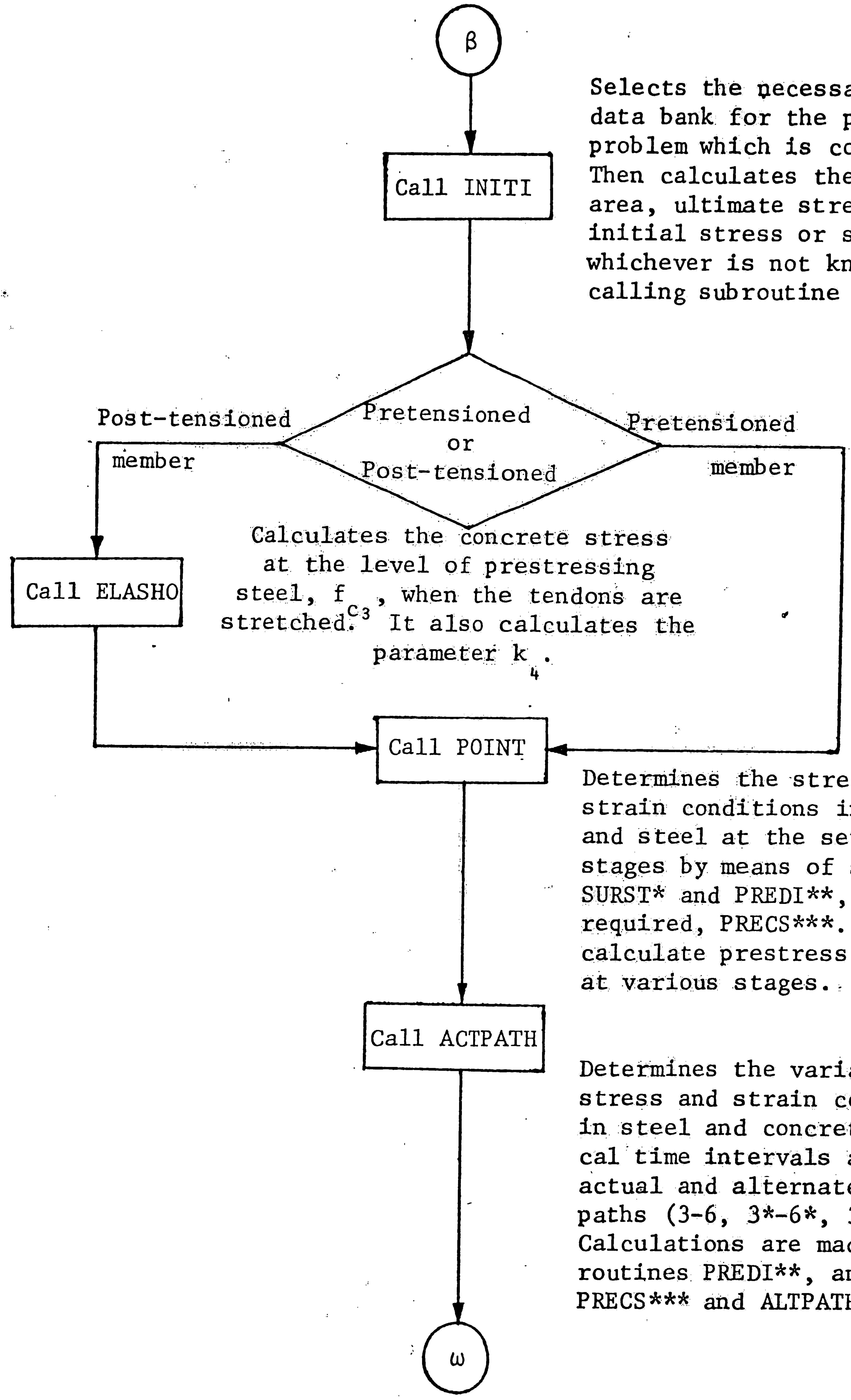
9. APPENDIX

APPENDIX

COMPUTER FLOW CHARTS AND PROGRAM




α
Read in total number of strands, gross area and moment of inertia of concrete section, and the distances of concrete fibers with reference to the centroid of the concrete section.
Pretensioned or Post-tensioned
Post-tensioned member
Pretensioned member
Read in the initial stress or strain of the strand, time interval from the end of curing period to post-tensioning and that from the prestressing of concrete to the application of loads, the applied load and bending moment.
Read in the initial stress or strain of the strand, time interval from tensioning of steel to transfer of prestress and that from transfer of prestress to application of loads, the applied load and bending moment.
Specify the levels where concrete strains and stresses are to be evaluated (optional).
β



Selects the necessary data from data bank for the particular problem which is concerned with. Then calculates the total steel area, ultimate strength, and initial stress or strain, whichever is not known, by calling subroutine SURST*.

Calculates the concrete stress at the level of prestressing steel, f_{c_3}, when the tendons are stretched. It also calculates the parameter k_4.

Determines the stress and strain conditions in concrete and steel at the several key stages by means of subroutines SURST* and PREDI**, and if required, PRECS***. Also calculate prestress losses at various stages.

Determines the variations of stress and strain conditions in steel and concrete at typical time intervals along the actual and alternate loading paths (3-6, 3*-6*, 3**-6**). Calculations are made by subroutines PREDI**, and if needed, PRECS*** and ALTPATH****.

* Call SURST	Steel stress-strain-time relationship. Determines the steel stress or strain whichever is not known at a given time.
** Call PREDI	Basic Prediction calculation as explained in Chapter 3. For any given time, the program evaluates parameters P, Q and R, solves the quadratic equations for g_1 and g_2 and calculates the steel and concrete stresses and strains.
*** Call PRECS	Calculates concrete stress and strain at each selected level (up to 5 levels).
**** Call ALTPATH	Provides calculation for the alternate paths 3*-6* and 3**-6**. Same types of calculations as mentioned in subroutine ACTPATH are given in this subroutine.

```
      PROGRAM PRELOSS (INPUT,OUTPUT)
C
C     PREDICTION METHOD FOR NON-UNIFORM PRETENSIONED OR POST-TENSIONED
C     SPECIMENS (SINGLE LAYER)
C
      COMMON / CONST / A1,A2,A3,B1,B2,B3,B4,C1,D1,D2,D3,D4,E1,E2,E3,E4,
     1                 NSUST,NSUCO,NTYST,NS,AGR,NAM(10),NNN,PPP,PMO,CMI,
     2                 ALP,BS,INDEX,AGE(23),TCP(10),TSP(10),FSP(10),
     3                 SSP(10),FCP(4,10),SCP(4,10),SCC(5,4),AST(22),
     4                 ACT(22),XXX(4),XST(5),FC3(5),IJK,NI,TTK4,AS(8),NS
     5                 AME
C
C                            INPUT FOR PROGRAM PRELOSS
C
C        FORMT   COLS.  SYMBOL    DESCRIPTION
C
C        CARD NO. 1   PRELOSS     FORMAT 1000
C        (ONE CARD)
C
C        I5      1-5    NSUST     STRESS-STRAIN-TIME RELATIONSHIP FOR
C                                 STRANDS OF VARIOUS MANUFACTURERS (A
C                                 CARD OF NSUST=0 SHOULD BE PROVIDED
C                                 AS THE LAST DATA CARD TO INDICATE
C                                 THE END OF PROBLEM)
C        I5      6-10   NSUCO     STRESS-STRAIN-TIME RELATIONSHIP FOR
C                                 CONCRETE OF VARIOUS MANUFACTURERS
C        I5      11-15  NTYST     TYPE OF STRANDS
C        I5      16-20  NI        SIGNAL USED TO CONTROL THE PROGRAM FOR
C                                 PRESTRESSED MEMBERS
C                                 1=FOR PRETENSIONED MEMBERS
C                                 0=FOR POST-TENSIONED MEMBERS
C
C        CARD NO. 2   PRELOSS     FORMAT 1001
C        (ONE CARD)
C
C        I5      1-5    NS        NUMBER OF STRANDS
C        F10.0   11-20  AGR       GROSS SECTION OF CONCRETE, IN IN.
C        F10.0   21-30  CMI       MOMENT OF INERTIA OF GROSS SECTION OF
C                                 CONCRETE, IN IN.4
C        F10.0   31-40  XXX(1)    THE DISTANCE FROM THE TOP FIBER WITH
C                                 REFERENCE TO THE CENTROID OF CONCRETE
C                                 SECTION, IN IN.
C        F10.0   41-50  XXX(2)    =0.0, CENTROID OF CONRETE GROSS SECTION
C                                 , IN IN.
C        F10.0   51-60  XXX(3)    THE DISTANCE FROM THE ECCENTRICITY OF
C                                 STRANDS WITH REFERENCE TO THE CENTROID
C                                 OF CONCRETE SECTION, IN IN.
C        F10.0   61-70  XXX(4)    THE DISTANCE FROM THE BOTTOM FIBER WITH
C                                 REFERENCE TO THE CENTROID OF CONRETE
C                                 SECTION, IN IN.
C
C        CARD NO. 3   PRELOSS     FORMAT 1002
C        (ONE CARD)
C
C        F10.0   1-10   FSP(I)    INITIAL STRESS IN STRAND(IN FRACTIONS
C                                 OF GUARANTEED ULTIMATE STRENGTH), IN
C                                 KSI
```

```
C                            FSP(1)   FOR PRETENSIONED MEMBERS
C                            FSP(2)   FOR POST-TENSIONED MEMBERS
C          F10.0    11-20    SSP(I)   INITIAL STRAIN OF STRAND, IN IN./IN.
C                            SSP(1)   FOR PRETENSIONED MEMBERS
C                            SSP(2)   FOR POST-TENSIONED MEMBERS
C          F10.0    21-30    TSP(3)   TIME INTERVAL BETWEEN STRETCHING AND
C                                     RELEASE OF STRANDS FOR PRETENSIONED
C                                     MEMBERS, IN DAYS
C                            TCP(3)   TIME INTERVAL FROM THE END OF CURING
C                                     TO POST-TENSIONING, IN DAYS
C          F10.0    31-40    TCP(5)   TIME INTERVAL BETWEEN RELEASE OF
C                                     STRANDS AND THE APPLICATION OF LOADS
C                                     FOR PRETENSIONED MEMBERS, IN DAYS
C                            TSP(5)   TIME INTERVAL BETWEEN RELEASE OF
C                                     STRANDS AND THE APPLICATION OF LOADS
C                                     FOR POST-TENSIONED MEMBERS, IN DAYS
C          F10.0    41-50    PPP      APPLIED AXIAL LOAD ON CONCRETE SECTION
C                                     , IN KIPS
C          F10.0    51-60    PMO      APPLIED BENDING MOMENT ON CONCRETE SEC-
C                                     TION, IN KIP-IN
C
C          CARD NO. 4   PRELOSS       FORMAT 1002
C          (ONE CARD)
C
C          5F10.0   1-50     XST(I)   THE DISTANCE FROM THE SELECTED LEVEL
C                                     WITH REFERENCE TO THE CENTROID OF CON-
C                                     CRETE SECTION, IN IN.
C
C          CARD NO. 5   ELASHO        FORMAT 1003
C          (ONE CARD)
C
C          I5       1-5      NSAME    SIGNAL USED TO CONTROL THE CASE WHEN
C                                     THE TENDONS ARE STRETCHED SIMULTA-
C                                     NEOUSLY OR IN SEQUENCES
C                                     =1 IF STRETCHED SIMULTANEOUSLY
C                                     =0 IF STRETCHED IN SEQUENCES
C
C          CARD NO. 6   ELASHO        FORMAT 1004
C          (ONE CARD)
C
C          F10.0    1-10     RN       MODULUS RATIO(THIS INPUT IS NOT  NECES-
C                                     SARY FOR THE TENDONS TO BE STRETCHED
C                                     SIMULTANEOUSLY)
C
C          CARD NO. 7   ELASHO        FORMAT 1004
C          (ONE CARD FOR EACH TIME    OF STRETCHING THE TENDONS)
C
C          F10.0    1-10     TNUMB    NUMBER OF TENDONS TO BE STRETCHED FOR
C                                     EACH TIME(A CARD OF TNUMB=0.0 SHOULD
C                                     BE PROVIDED TO INDICATE END OF PROBLEM
C                                     , BUT NOT NECESSARY FOR THE CASE WHEN
C                                     THE TENDONS ARE STRETCHED SIMULTA-
C                                     NEOUSLY )
C
  100 READ 1000, NSUST,NSUCO,NTYST,NI
      IF (NSUST .EQ. 0) GO TO 800
      READ 1001, NS,AGR,CMI,(XXX(L),L=1,4)
      IF (NI .EQ. 0) GO TO 48
```

```
      READ 1002,FSP(1),SSP(1),TSP(3),TCP(5),PPP,PMO
      GO TO 489
   48 READ 1002,FSP(2),SSP(2),TCP(3),TSP(5),PPP,PMO
  489 READ 1002, (XST(L),L=1,5)
      CALL INITI
      IF (NI .EQ. C) CALL ELASHO
      CALL POINT
      CALL ACTPATH
      GO TO 100
  800 CALL EXIT
 1000 FORMAT (4I5)
 1001 FORMAT (I5,5X,6F10.0)
 1002 FORMAT (6F10.0)
      END


      SUBROUTINE ELASHO
C
C     CALCULATE THE CONCRETE STRESS AT THE LEVEL OF PRESTRESSING STEEL
C     AND THE PARAMETER K4 FOR POST-TENSIONED MEMBERS ONLY
C
      COMMON / CONST / A1,A2,A3,B1,B2,B3,B4,C1,D1,D2,D3,D4,E1,E2,E3,E4,
     1                 NSUST,NSUCO,NTYST,NS,AGR,NAM(10),NNN,PPP,PMO,CMI,
     2                 ALP,BS,INDEX,AGE(23),TCP(10),TSP(10),FSP(10),
     3                 SSP(10),FCP(4,10),SCP(4,10),SCC(5,4),AST(22),
     4                 ACT(22),XXX(4),XST(5),FC3(5),IJK,NI,TTK4,AS(8),NS
     5                 AME
      PRENU=0.0
      FFC3=0.0
      NCOUNT=1
      READ 1003, NSAME
      IF (NSAME .EQ. 1) GO TO 124
      READ 1004, RN
  124 READ 1004, TNUMB
      IF (TNUMB .EQ. 0.0) GO TO 242
      TOAS=TNUMB*AS(NTYST)
      AXTS=TOAS*FSP(IJK)*ALP
      IF (NCOUNT .GT. 1) GO TO 789
      AN=AGR-BS
      XSBOT=XXX(4)-XXX(3)
      YN=(AGR*(XXX(4))-BS*XSBOT)/AN
      EN=YN-XSBOT
      XCGR=XXX(4)-YN
      ENSQ=EN*EN
      CMIN=CMI+AGR*XCGR*XCGR-BS*ENSQ
      STRES3=AXTS/AN+(AXTS*ENSQ)/CMIN
      GO TO 998
  789 PRENU=TNUMB+PRENU
      PRODT=(RN-1.0)*(NS-PRENU)*AS(NTYST)
      AT=AGR-TNUMB*AS(NTYST)+PRODT
      PNI=(PRODT*XXX(3))/AT
      ET=XXX(3)-PNI
      CMIT=CMI+AGR*XXX(3)*PNI
      STRES3=AXTS/AT+(AXTS*ET*ET)/CMIT
  998 FFC3=STRES3+FFC3
      IF (NSAME .EQ. 1) GO TO 244
      NCOUNT=NCOUNT+1
```

```
      GO TO 124
  242 ALPHA=0.5
      GO TO 245
  244 ALPHA=0.0
  245 TIMM=ALOG10(TCP(3)+1.0)
      QQ1=D1+D2*TIMM
      TTK4=QQ1+SSP(2)+(1.0-ALPHA)*C1*FFC3
      RETURN
 1003 FORMAT(I5)
 1004 FORMAT(F10.0)
      END



      SUBROUTINE INITI
C
C     INITIALIZATION AND SELECTION OF COEFFICIENTS
C
      COMMON / CONST / A1,A2,A3,B1,B2,B3,B4,C1,D1,D2,D3,D4,E1,E2,E3,E4,
     1                 NSUST,NSUCO,NTYST,NS,AGR,NAM(10),NNN,PPP,PMO,CMI,
     2                 ALP,BS,INDEX,AGE(23),TCP(10),TSP(10),FSP(10),
     3                 SSP(10),FCP(4,10),SCP(4,10),SCC(5,4),AST(22),
     4                 ACT(22),XXX(4),XST(5),FC3(5),IJK,NI,TTK4,AS(8),NS
     5                 AME
      DIMENSION BB1(13),BB2(13),BB3(13),BB4(13),CC1(12),DD1(12),DD2(12),
     1          EE1(12),EE2(12),EE3(12),EE4(12),NUM(2),LAST(8),NAST(13),
     2          NACO(24),FSU(8)
      DATA A1,A2,A3            / -4.22877E-02,1.21952E+00,-1.78268E-01 /
      DATA (BB1(L),L=1,13)   / -5.243505E-02,-4.696932E-02,-6.035769E-02,
     1                         -6.380430E-02,-7.880080E-02,-6.921702E-02,
     2                         -5.321263E-02,-7.346071E-02,-5.867267E-02,
     3                         -4.122982E-03,-2.671631E-02,-1.402721E-02,
     4                          0.0 /
      DATA (BB2(L),L=1,13)   /  1.132333E-03,-1.172892E-02, 8.910628E-03,
     1                          3.591552E-03,-7.619116E-03, 8.435512E-03,
     2                          2.914934E-03, 6.196370E-03, 2.294611E-04,
     3                          1.421067E-03, 1.399884E-02, 6.093485E-03,
     4                          0.0 /
      DATA (BB3(L),L=1,13)   /  1.150196E-01, 1.001503E-01, 1.206775E-01,
     1                          1.203677E-01, 1.459753E-01, 1.364500E-01,
     2                          1.129406E-01, 1.384711E-01, 1.185984E-01,
     3                          2.202793E-02, 4.434756E-02, 3.244550E-02,
     4                          0.0 /
      DATA (BB4(L),L=1,13)   /  5.228071E-02, 5.943141E-02, 2.659559E-02,
     1                          5.673333E-02, 5.920295E-02, 4.393948E-02,
     2                          3.762833E-02, 4.608148E-02, 4.857612E-02,
     3                          1.605362E-02, 9.228446E-03, 1.395361E-02,
     4                          0.0 /
      DATA (CC1(L),L=1,12)   / 4000.,4750.,4350.,4000.,4750.,4350.,
     1                         4000.,4750.,4350.,4000.,4750.,4350. /
      DATA (DD1(L),L=1,12)   / -6.682990E-03,-6.568803E-04,-2.886724E-03,
     1                         -6.682990E-03,-6.568803E-04,-2.886724E-03,
     2                         -0.          ,-0.          ,-0.          ,
     3                         -0.          ,-0.          ,-0.          /
      DATA (DD2(L),L=1,12)   /  2.453774E-02, 1.500002E-02, 2.031301E-02,
     1                          2.453774E-02, 1.500002E-02, 2.031301E-02,
     2                         -0.          ,-0.          ,-0.          ,
     3                         -0.          ,-0.          ,-0.          /
```

```
      DATA (EE1(L),L=1,12)  / -1.280123E-02,-6.640735E-03,-1.591966E-02,
     1                        -0.          ,-0.          ,-0.          ,
     2                        -1.280123E-02,-6.640735E-03,-1.591966E-02,
     3                        -0.          ,-0.          ,-0.          /
      DATA (EE2(L),L=1,12)  /  6.754405E-03,-3.313725E-03, 6.488917E-03,
     1                        -0.          ,-0.          ,-0.          ,
     2                         6.754405E-03,-3.313725E-03, 6.488917E-03,
     3                        -0.          ,-0.          ,-0.          /
      DATA (EE3(L),L=1,12)  / -5.980912E-04,-3.706964E-03, 2.560218E-03,
     1                        -0.          ,-0.          ,-0.          ,
     2                        -5.980912E-04,-3.706964E-03, 2.560218E-03,
     3                        -0.          ,-0.          ,-0.          /
      DATA (EE4(L),L=1,12)  /  1.609097E-02, 1.408682E-02, 1.153427E-02,
     1                        -0.          ,-0.          ,-0.          ,
     2                         1.609097E-02, 1.408682E-02, 1.153427E-02,
     3                        -0.          ,-0.          ,-0.          /
      DATA (AGE(L),L=1,23)  / 1.,2.,3.,5.,7.,10.,20.,30.,50.,70.,
     1                        100.,200.,300.,500.,700.,1000.,1500.,
     2                        3000.,5000.,7000.,10000.,20000.,36500. /
      DATA (FSU(L),L=1,8)   / 31.,31.,31.,41.3,41.3,41.3,31.,41.3 /
      DATA (AS(L),L=1,8)    / .115,.117,.1155,.156,.153,.1535,.117,.153/
      DATA (LAST(L),L=1,8)  / 10HBET   7/16,10HCFI   7/16,10HUSS   7/16,
     1                        10HBET    1/2,10HCFI    1/2,10HUSS    1/2,
     2                        10HLOK   7/16,10HLOK    1/2 /
      DATA (NAST(L),L=1,13) / 10HAB5 - AB7 ,10HAC5 - AC8 ,10HAU5 - AU8 ,
     1                        10HBB5 - BB8 ,10HBC5 - BC8 ,10HBU5 - BU8 ,
     2                        10HAB5 - AU8 ,10HBB5 - BU8 ,10HAB5 - BU8 ,
     3                        10HLC6 - LC8 ,10HKC6 - KC8 ,10HLC6 - KC8 ,
     4                        10HOCO - 000 /
      DATA (NACO(L),L=1,24) / 10HAA - PA   ,10HAC - PC   ,10HAA - PC   ,
     1                        10HAA - PA   ,10HAC - PC   ,10HAA - PC   ,
     2                        10HAA - PA   ,10HAC - PC   ,10HAA - PC   ,
     3                        10HAA - PA   ,10HAC - PC   ,10HAA - PC   ,
     4                        10H          ,10H          ,10H          ,
     5                        10H      NOCR,10H      NOCR,10H      NOCR,
     6                        10H      NOSH,10H      NOSH,10H      NOSH,
     7                        10H    NOCRSH,10H    NOCRSH,10H    NOCRSH/
      DATA (NAM(L),L=1,10)  / 3H  1,3H  2,3H  3,3H  4,3H  5,3H  6,3H 3*,
     1                        3H 6*,3H3**,3H6**/
      DATA (NUM(L),L=1,2)   / 6,4 /
      DATA IEE,IFF,IJJ,ILL,IPP,IQQ / 3HTS3,3HTC3,2HK1,2HK3,3HTC5,3HTS5 /
      IJK=2-NI
      IF (NI.EQ.0) GO TO 779
      GO TO 707
  779 IEE=IFF  $  IJJ=ILL  $  IPP=IQQ
C     INDEX=1 FOR LOADING CASE
C     INDEX=2 FOR UNLOADING CASE
  707 INDEX=1
      IF ((PPP .EQ. 0.0) .AND. (PMO .EQ. 0.0)) INDEX=2
      NNN=NUM(INDEX)
      B1=BB1(NSUST)
      B2=BB2(NSUST)
      B3=BB3(NSUST)
      B4=BB4(NSUST)
      C1=100.0/CC1(NSUCO)
      D1=DD1(NSUCO)
      D2=DD2(NSUCO)
      E1=EE1(NSUCO)
```

```
      E2=EE2(NSUCO)
      E3=EE3(NSUCO)
      E4=EE4(NSUCO)
      DO 100 J=1,22
      IF (NI.EQ.0) GO TO 605
      AST(J)=AGE(J)+TSP(3)
      GO TO 100
  605 ACT(J)=AGE(J)+TCP(3)
  100 CONTINUE
      BS=NS*AS(NTYST)
      ALP=FSU(NTYST)/AS(NTYST)
      IF (FSP(IJK) .EQ. 0.0) CALL FFF(FSP(IJK),SSP(IJK),0.0)
      IF (SSP(IJK) .EQ. 0.0) CALL SSS(FSP(IJK),SSP(IJK),0.0)
      IF (NI.EQ. 0) GO TO 488
      TIME3=TSP(3)  $  TIME5=TCP(5)
      GO TO 169
  488 TIME3=TCP(3)  $  TIME5=TSP(5)
  169 PRINT 2000, NAST(NSUST)
      PRINT 2001, NACO(NSUCO),NACO(NSUCO+12)
      PRINT 2002, LAST(NTYST)
      PRINT 2003, NS,BS,XXX(3),AGR,CMI,XXX(1),XXX(4),IJJ,IEE,TIME3,IJK,S
     1            SP(IJK),IJK,FSP(IJK),PPP,PMO,IPP,TIME5
      RETURN
 2000 FORMAT (1H1////15X*TYPE OF STEEL SURFACE*10X*:*3X,A9)
 2001 FORMAT (///15X*TYPE OF CONCRETE SURFACE*7X*:*3X,2A10)
 2002 FORMAT (///15X*TYPE OF PRESTRESSING STRANDS   :*3X,A10)
 2003 FORMAT (///15X*NS  =*I18//15X*AS  =*F18.4//15X*XS  =*F18.4////15X
     1*AC  =*F18.4//15X*IC  =*F18.4//15X*XTOP=*F18.4//15X*XBOT=*F18.4///
     2//15XA2*  =  *A3,*  =*F10.4//15X*K2  =  SS*I1,*  =*F10.4,20X*FS*I1
     3,*  =*F10.4/////15X*P   =*F18.2//15X*M   =*F18.2//15XA3* =*F18.2)
      END


      SUBROUTINE PREDI (TS,P,PM,FS,SS,FC,SC)
C
C     PREDICTED VALUES OF STRESS AND STRAIN IN STEEL
C
      COMMON / CONST / A1,A2,A3,B1,B2,B3,B4,C1,D1,D2,D3,D4,E1,E2,E3,E4,
     1                 NSUST,NSUCO,NTYST,NS,AGR,NAM(10),NNN,PPP,PMO,CMI,
     2                 ALP,BS,INDEX,AGE(23),TCP(10),TSP(10),FSP(10),
     3                 SSP(10),FCP(4,10),SCP(4,10),SCC(5,4),AST(22),
     4                 ACT(22),XXX(4),XST(5),FC3(5),IJK,NI,TTK4,AS(8),NS
     5                 AME
      COMMON / COEFF / Q1,Q2,G1,G2
      DIMENSION FC(1),SC(1)
      TIM=ALOG10(TS+1.0)
      P1=ALP*A1
      IF ((NI .EQ. 0) .AND. (TS .EQ. 0.0)) GO TO 108
      P2=ALP*(A2-B1-B2*TIM)
      P3=ALP*(A3-B3-B4*TIM)
      IF (NI .EQ. 0) GO TO 281
      GO TO 233
  108 P2=ALP*A2  $  P3=ALP*A3
      GO TO 281
  233 IF (TS .EQ. TSP(3)) GO TO 100
      TIM=ALOG10(TS-TSP(3)+1.0)
      Q1=D1+E1+(D2+E2)*TIM
```

```
      GO TO 601
  281 TIME=ALOG10(TS+TCP(3)+1.0)
      QQ1=D1+D2*TIME
      IF (TS .EQ. 0.0) GO TO 602
      Q1=QQ1+E1+E2*TIM
  601 Q2=C1+E3+E4*TIM
      IF (NI .EQ. 1) GO TO 101
      GO TO 858
  602 Q1=QQ1
  100 IF (NI .EQ. 1) Q1=0.0
      Q2=C1
      IF (NI .EQ. 0) GO TO 858
  101 DUM=SSP(1)-Q1
      GO TO 774
  858 DUM=TTK4-Q1
  774 R1=P1+P2*DUM+P3*DUM*DUM
      R2=-Q2*(P2+2.0*P3*DUM)
      R3=P3*Q2*Q2
      CG1=-(P*XXX(3)+PM)/CMI
      CG2=AGR*XXX(3)/CMI
      AAA=R2+1.0
      BBB=BS*XXX(3)*CG1
      CCC=XXX(3)*CG2+1.0
      W1=R1*BS+P+AAA*BBB+R3*BBB*XXX(3)*CG1
      W2=(AAA*BS+2.0*R3*BBB)*CCC-AGR
      W3=R3*BS*CCC*CCC
      DDD=W2*W2-4.0*W1*W3
      IF (DDD .GT. 0.0) GO TO 102
      PRINT 2000
      CALL EXIT
  102 CONTINUE
      G1=(-W2+SQRT(DDD))/(2.0*W3)
      IF (G1 .LT. 0.0) G1=(-W2-SQRT(DDD))/(2.0*W3)
      G2=CG1+CG2*G1
      DO 103 I=1,4
      FC(I)=G1+G2*XXX(I)
      SC(I)=Q1+Q2*FC(I)
  103 CONTINUE
      IF (NI.EQ. 0) GO TO 1208
      SS=SSP(1)-SC(3)
      GO TO 1209
 1208 SS=TTK4-SC(3)
 1209 FS=(R1+R2*FC(3)+R3*FC(3)*FC(3))/ALP
      RETURN
 2000 FORMAT (*1*///10X*IMPROPER SOLUTION OF QUADRATIC EQUATION*)
      END


      SUBROUTINE POINT
C
C     PREDICTED VALUES AT INITIAL STRETCHING, RELEASE, LOADING,
C     AND ULTIMATE
C
      COMMON / CONST / A1,A2,A3,B1,B2,B3,B4,C1,D1,D2,D3,D4,E1,E2,E3,E4,
     1                 NSUST,NSUCO,NTYST,NS,AGR,NAM(10),NNN,PPP,PMO,CMI,
     2                 ALP,BS,INDEX,AGE(23),TCP(10),TSP(10),FSP(10),
     3                 SSP(10),FCP(4,10),SCP(4,10),SCC(5,4),AST(22),
```

```
     4                        ACT(22),XXX(4),XST(5),FC3(5),IJK,NI,TTK4,AS(8),NS
     5                        AME
      DIMENSION DUM(5)
      IF (NI .EQ. 0) GO TO 707
      TCP(1)=TCP(2)=TCP(3)=TSP(1)=0.0
      TSP(2)=TSP(3)
      SSP(2)=SSP(1)
      CALL FFF(FSP(2),SSP(1),TSP(2))
      GO TO 708
  707 TSP(1)=TSP(2)=TSP(3)=TCP(1)=0.0
      TCP(2)=TCP(3)
      FSP(1)=SSP(1)=0.0
      KJJ=2
  708 IF (NI .EQ. 0) KJJ=1
      DO 99 I=1,4
      DO 99 J=1,KJJ
   99 FCP(I,J)=SCP(I,J)=0.0
      CALL PREDI (TSP(3),0.0,0.0,FSP(3),SSP(3),FCP(1,3),SCP(1,3))
      IF (XST(1) .NE. 0.0) CALL PRECS (SCC(1,1),FC3)
      GO TO (100,102) INDEX
  100 IF (NI .EQ. 0) GO TO 483
      TCP(4)=TCP(5)
      TCP(7)=TCP(9)=0.0
      TCP(6)=TCP(8)=TCP(10)=36500.0
      GO TO 178
  483 TSP(4)=TSP(5)
      TSP(7)=TSP(9)=0.0
      TSP(6)=TSP(8)=TSP(10)=36500.0
  178 DO 101 I=4,10
      IF (NI .EQ. 0) GO TO 712
      TSP(I)=TCP(I)+TSP(3)
      GO TO 101
  712 TCP(I)=TCP(3)+TSP(I)
  101 CONTINUE
      CALL PREDI (TSP(4),0.0,0.0,FSP(4),SSP(4),FCP(1,4),SCP(1,4))
      IF (XST(1) .NE. 0.0) CALL PRECS (SCC(1,2),DUM)
      CALL PREDI (TSP(8),0.0,0.0,FSP(8),SSP(8),FCP(1,8),SCP(1,8))
      FSP(7)=FSP(3)
      SSP(7)=SSP(3)
      DO 500 I=1,4
      FCP(I,7)=FCP(I,3)
  500 SCP(I,7)=SCP(I,3)
      DO 201 I=9,10
  201 CALL PREDI (TSP(I),PPP,PMO,FSP(I),SSP(I),FCP(1,I),SCP(1,I))
      DO 202 I=5,6
      CALL PREDI (TSP(I),PPP,PMO,FSP(I),SSP(I),FCP(1,I),SCP(1,I))
      IF (XST(1) .NE. 0.0) CALL PRECS(SCC(1,I-2),DUM)
  202 CONTINUE
      GO TO 103
  102 IF (NI .EQ. 0) GO TO 714
      TCP(4)=36500.0
      TSP(4)=TCP(4)+TSP(3)
      GO TO 715
  714 TSP(4)=36500,0
      TCP(4)=TSP(4)+TCP(3)
  715 CALL PREDI (TSP(4),0.0,0.0,FSP(4),SSP(4),FCP(1,4),SCP(1,4))
      IF (XST(1) .NE. 0.0) CALL PRECS(SCC(1,2),DUM)
  103 DIF=FSP(IJK)-FSP(NNN)
```

```
      PRINT 2000,IJK,IJK,IJK,IJK,IJK,NNN
      DO 104 I=1,NNN
      IF ((I .LE. 2) .AND. (NI .EQ. 0)) GO TO 104
      DEL=FSP(IJK)-FSP(I)
      DTA=DEL/FSP(IJK)
      FRA=DEL/DIF
      PRINT 2001, NAM(I),TCP(I),TSP(I),FSP(I),SSP(I),DEL,DTA,FRA
  104 CONTINUE
      GO TO (105,107) INDEX
  105 DO 106 I=7,10,2
      PRINT 2002
      J=I+1
      DEL=FSP(IJK)-FSP(I)
      DTA=DEL/FSP(IJK)
      FRA=DEL/DIF
      PRINT 2001, NAM(I),TCP(I),TSP(I),FSP(I),SSP(I),DEL,DTA,FRA
      DEL=FSP(IJK)-FSP(J)
      DTA=DEL/FSP(IJK)
      FRA=DEL/DIF
      PRINT 2001, NAM(J),TCP(J),TSP(J),FSP(J),SSP(J),DEL,DTA,FRA
  106 CONTINUE
  107 PRINT 2002
      PRINT 2003
      DO 108 J=1,NNN
      IF ((J .LE. 2) .AND. (NI .EQ. 0)) GO TO 108
      PRINT 2004, NAM(J),TCP(J),TSP(J),((FCP(I,J),SCP(I,J)),I=1,4)
  108 CONTINUE
      GO TO (109,800) INDEX
  109 DO 300 J=7,10,2
      PRINT 2002
      K=J+1
      PRINT 2004, ((NAM(L),TCP(L),TSP(L),((FCP(I,L),SCP(I,L)),I=1,4)),L=
     1            J,K)
  300 CONTINUE
  800 RETURN
 2000 FORMAT (1H1//11X*X = XS*////104X*FS*I1,* - FS*8X*FS*I1,* - FS*/11X
     1*POINT*14X*TC*14X*TS*14X*FS*14X*SS*9X*FS*I1,* - FS*8X*--------*7X*
     2---------*/107X*FS*I1,9X*FS*I1,* - FS*I1//)
 2001 FORMAT (11X,A3,2X,2F16.2,5F16.4)
 2002 FORMAT (/)
 2003 FORMAT (///50X*X =XTOP*17X*X = 0*19X*X = XS*17X*X = XBOT*//7X*POIN
     1T*10X*TC*10X*TS*4(10X*FC*10X*SC*)//)
 2004 FORMAT (7X,A3,2X,2F12.2,8F12.4)
      END


      SUBROUTINE ACTPATH
C
C     LOADING PATH      3 - 6 (FOR PRETENSIONING OR FOR POST-TENSIONING)
C
      COMMON / CONST / A1,A2,A3,B1,B2,B3,B4,C1,D1,D2,D3,D4,E1,E2,E3,E4,
     1                 NSUST,NSUCO,NTYST,NS,AGR,NAM(10),NNN,PPP,PMO,CMI,
     2                 ALP,BS,INDEX,AGE(23),TCP(10),TSP(10),FSP(10),
     3                 SSP(10),FCP(4,10),SCP(4,10),SCC(5,4),AST(22),
     4                 ACT(22),XXX(4),XST(5),FC3(5),IJK,NI,TTK4,AS(8),NS
     5                 AME
      DIMENSION DEL(2,4),DTA(2,4),FRA(2,4),DIF(2),SCS(5,22)
```

```
      DIMENSION FCT(4,22),SCT(4,22),DUM(5)
      LAB=3H
      IF (INDEX .EQ. 2) GO TO 101
      DO 100 J=1,22
      IF (NI .EQ. 0) GO TO 811
      IF (AGE(J) .LT. TCP(5)) GO TO 100
      GO TO 813
  811 IF (AGE(J) .LT. TSP(5)) GO TO 100
  813 JJJ=J-1
      KKK=J
      IF (NI .EQ. 0) GO TO 812
      IF (AGE(J) .EQ. TCP(5)) KKK=J+1
      GO TO 102
  812 IF (AGE(J) .EQ. TSP(5)) KKK=J+1
      GO TO 102
  100 CONTINUE
  101 JJJ=22
  102 PRINT 2000, NNN,IJK,IJK,IJK,IJK,IJK,NNN,IJK,NNN
      DIF(1)=FSP(IJK)-FSP(NNN)
      DIF(2)=FSP(3)-FSP(NNN)
      DO 103 I=3,NNN
      L=I-2
      DEL(1,L)=FSP(IJK)-FSP(I)
      DTA(1,L)=DEL(1,L)/FSP(IJK)
      FRA(1,L)=DEL(1,L)/DIF(1)
      DEL(2,L)=FSP(3)-FSP(I)
      DTA(2,L)=DEL(2,L)/FSP(IJK)
      FRA(2,L)=DEL(2,L)/DIF(2)
  103 CONTINUE
      PRINT 2001, NAM(3),TCP(3),TSP(3),FSP(3),SSP(3),
     1               ((DEL(I,1),DTA(I,1),FRA(I,1)),I=1,2)
      PRINT 2002
      DO 104 J=1,JJJ
      IF (NI .EQ. 0) GO TO 277
      CALL PREDI (AST(J),0.0,0.0,FS,SS,FCT(1,J),SCT(1,J))
      GO TO 278
  277 CALL PREDI (AGE(J),0.0,0.0,FS,SS,FCT(1,J),SCT(1,J))
  278 IF (XST(1) .NE. 0.0) CALL PRECS (SCS(1,J),DUM)
      AAA=FSP(IJK)-FS
      BBB=AAA/FSP(IJK)
      CCC=AAA/DIF(1)
      DDD=FSP(3)-FS
      EEE=DDD/FSP(IJK)
      FFF=DDD/DIF(2)
      IF (NI .EQ. 0) GO TO 279
      PRINT 2001, LAB,AGE(J),AST(J),FS,SS,AAA,BBB,CCC,DDD,EEE,FFF
      GO TO 104
  279 PRINT 2001, LAB,ACT(J),AGE(J),FS,SS,AAA,BBB,CCC,DDD,EEE,FFF
  104 CONTINUE
      PRINT 2002
      PRINT 2001, NAM(4),TCP(4),TSP(4),FSP(4),SSP(4),
     1               ((DEL(I,2),DTA(I,2),FRA(I,2)),I=1,2)
      GO TO (105,200) INDEX
  105 PRINT 2002
      PRINT 2001, NAM(5),TCP(5),TSP(5),FSP(5),SSP(5),
     1               ((DEL(I,3),DTA(I,3),FRA(I,3)),I=1,2)
      PRINT 2002
      DO 106 J=KKK,22
```

```
      IF (NI .EQ. 0) GO TO 280
      CALL PREDI (AST(J),PPP,PMO,FS,SS,FCT(1,J),SCT(1,J))
      GO TO 281
  280 CALL PREDI (AGE(J),PPP,PMO,FS,SS,FCT(1,J),SCT(1,J))
  281 IF (XST(1) .NE. 0.0) CALL PRECS (SCS(1,J),DUM)
      AAA=FSP(IJK)-FS
      BBB=AAA/FSP(IJK)
      CCC=AAA/DIF(1)
      DDD=FSP(3)-FS
      EEE=DDD/FSP(IJK)
      FFF=DDD/DIF(2)
      IF (NI .EQ. 0) GO TO 282
      PRINT 2001, LAB,AGE(J),AST(J),FS,SS,AAA,BBB,CCC,DDD,EEE,FFF
      GO TO 106
  282 PRINT 2001, LAB,ACT(J),AGE(J),FS,SS,AAA,BBB,CCC,DDD,EEE,FFF
  106 CONTINUE
      PRINT 2002
      PRINT 2001, NAM(6),TCP(6),TSP(6),FSP(6),SSP(6),
     1            ((DEL(I,4),DTA(I,4),FRA(I,4)),I=1,2)
  200 PRINT 2003, NNN
      PRINT 2001, NAM(3),TCP(3),TSP(3),
     1            ((FCP(I,3),SCP(I,3)),I=1,4)
      PRINT 2002
      DO 201 J=1,JJJ
      IF (NI .EQ. 0) GO TO 283
      PRINT 2001, LAB,AGE(J),AST(J),((FCT(I,J),SCT(I,J)),I=1,4)
      GO TO 201
  283 PRINT 2001, LAB,ACT(J),AGE(J),((FCT(I,J),SCT(I,J)),I=1,4)
  201 CONTINUE
      PRINT 2002
      PRINT 2001, NAM(4),TCP(4),TSP(4),
     1            ((FCP(I,4),SCP(I,4)),I=1,4)
      GO TO (202,300) INDEX
  202 PRINT 2002
      PRINT 2001, NAM(5),TCP(5),TSP(5),
     1            ((FCP(I,5),SCP(I,5)),I=1,4)
      PRINT 2002
      DO 203 J=KKK,22
      IF (NI .EQ. 0) GO TO 284
      PRINT 2001, LAB,AGE(J),AST(J),((FCT(I,J),SCT(I,J)),I=1,4)
      GO TO 203
  284 PRINT 2001, LAB,ACT(J),AGE(J),((FCT(I,J),SCT(I,J)),I=1,4)
  203 CONTINUE
      PRINT 2002
      PRINT 2001, NAM(6),TCP(6),TSP(6),
     1            ((FCP(I,6),SCP(I,6)),I=1,4)
  300 CONTINUE
      IF (XST(1) .EQ. 0.0) GO TO 400
      PRINT 2005,NNN,(XST(L),L=1,5)
      PRINT 2006, TCP(3),TSP(3),(FC3(L),L=1,5)
      DO 305 I=1,5
      DO 305 J=1,22
  305 SCS(I,J)=SCS(I,J)-SCC(I,1)
      DO 304 I=1,5
      CON=SCC(I,1)
      DO 304 J=1,4
  304 SCC(I,J)=SCC(I,J)-CON
      PRINT 2004, NAM(3),TCP(3),TSP(3),(SCC(L,1),L=1,5)
```

```
      PRINT 2002
      DO 301 J=1,JJJ
      IF (NI .EQ. 0) GO TO 285
      PRINT 2004, LAB,AGE(J),AST(J),(SCS(L,J),L=1,5)
      GO TO 301
  285 PRINT 2004, LAB,ACT(J),AGE(J),(SCS(L,J),L=1,5)
  301 CONTINUE
      PRINT 2002
      PRINT 2004, NAM(4),TCP(4),TSP(4),(SCC(L,2),L=1,5)
      GO TO (302,800) INDEX
  302 PRINT 2002
      PRINT 2004, NAM(5),TCP(5),TSP(5),(SCC(L,3),L=1,5)
      PRINT 2002
      DO 303 J=KKK,22
      IF (NI .EQ. 0) GO TO 286
      PRINT 2004, LAB,AGE(J),AST(J),(SCS(L,J),L=1,5)
      GO TO 303
  286 PRINT 2004, LAB,ACT(J),AGE(J),(SCS(L,J),L=1,5)
  303 CONTINUE
      PRINT 2002
      PRINT 2004, NAM(6),TCP(6),TSP(6),(SCC(L,4),L=1,5)
  400 CONTINUE
      GO TO (500,800,500,800),INDEX
  500 CALL ALTPATH
  800 RETURN
 2000 FORMAT (1H1///7X*X = XS*////7X*LOADING PATH*10X*3 - *I1/////76X*FS
     1*I1,* - FS*4X*FS*I1,* - FS*16X*FS3 - FS*4X*FS3 - FS*/7X*POINT*10X*
     2TC*10X*TS*10X*FS*10X*SS*4X*FS*I1,* - FS*4X*--------*3X*---------*4
     3X*FS3 - FS*4X*--------*3X*---------*/79X*FS*I1,2X,3X*FS*I1,* - FS*
     4I1,19X*FS*I1,5X*FS3 - FS*I1///)
 2001 FORMAT (7X,A3,2X,2F12.2,8F12.4)
 2002 FORMAT (/)
 2003 FORMAT (1H1///7X*LOADING PATH*10X*3 - *I1/////49X*X = XTOP*17X*X =
     1 0*19X*X = XS*17X*X = XBOT*//7X*POINT*10X*TC*10X*TS*4(10X*FC*10X*S
     2C*)////)
 2004 FORMAT (11X,A3,2X,2F16.2,5F16.4)
 2005 FORMAT (1H1//11X*LOADING PATH*10X*3 - *I1//11X*SC - SC3     VALU
     1ES*             ////11X*POINT*14X*TC*14X*TS*5(6X*X =*F7.2)///)
 2006 FORMAT (11X*FC3  *2F16.2,5F16.4///)
      END


      SUBROUTINE ALTPATH
C
C     (A)      LOADING PATH     3* - 6*
C     (B)      LOADING PATH     3** - 6**
C
      COMMON / CONST / A1,A2,A3,B1,B2,B3,B4,C1,D1,D2,D3,D4,E1,E2,E3,E4,
     1                 NSUST,NSUCO,NTYST,NS,AGR,NAM(10),NNN,PPP,PMO,CMI,
     2                 ALP,BS,INDEX,AGE(23),TCP(10),TSP(10),FSP(10),
     3                 SSP(10),FCP(4,10),SCP(4,10),SCC(5,4),AST(22),
     4                 ACT(22),XXX(4),XST(5),FC3(5),IJK,NI,TTK4,AS(8),NS
     5                 AME
      DIMENSION DIF(2),DEL(2),DTA(2),FRA(2)
      DIMENSION FCT(4,22),SCT(4,22)
      LAB=3H
      P=0.0
```

```
      PM=0.0
      KKK=3
      IF (INDEX .EQ. 1) KKK=7
  100 LLL=KKK+1
      DIF(1)=FSP(IJK)-FSP(LLL)
      DIF(2)=FSP(KKK)-FSP(LLL)
      DEL(1)=FSP(IJK)-FSP(KKK)
      DTA(1)=DEL(1)/FSP(IJK)
      FRA(1)=DEL(1)/DIF(1)
      DEL(2)=DTA(2)=FRA(2)=0.0
      PRINT 2000, NAM(KKK),NAM(LLL),IJK,IJK,IJK,IJK,IJK,NNN,IJK,NNN
      PRINT 2001, NAM(KKK),TCP(KKK),TSP(KKK),FSP(KKK),SSP(KKK),
     1            ((DEL(L),DTA(L),FRA(L)),L=1,2)
      PRINT 2002
      DO 101 J=1,22
      IF (NI .EQ. 0) GO TO 287
      CALL PREDI (AST(J),P,PM,FS,SS,FCT(1,J),SCT(1,J))
      GO TO 288
  287 CALL PREDI (AGE(J),P,PM,FS,SS,FCT(1,J),SCT(1,J))
  288 DEL(1)=FSP(IJK)-FS
      DTA(1)=DEL(1)/FSP(IJK)
      FRA(1)=DEL(1)/DIF(1)
      DEL(2)=FSP(KKK)-FS
      DTA(2)=DEL(2)/FSP(IJK)
      FRA(2)=DEL(2)/DIF(2)
      IF (NI .EQ. 0) GO TO 289
      PRINT 2001, LAB,AGE(J),AST(J),FS,SS,((DEL(L),DTA(L),FRA(L)),L=1,2)
      GO TO 101
  289 PRINT 2001, LAB,ACT(J),AGE(J),FS,SS,((DEL(L),DTA(L),FRA(L)),L=1,2)
  101 CONTINUE
      PRINT 2002
      DEL(1)=FSP(IJK)-FSP(LLL)
      DTA(1)=DEL(1)/FSP(IJK)
      FRA(1)=DEL(1)/DIF(1)
      DEL(2)=FSP(KKK)-FSP(LLL)
      DTA(2)=DEL(2)/FSP(IJK)
      FRA(2)=DEL(2)/DIF(2)
      PRINT 2001, NAM(LLL),TCP(LLL),TSP(LLL),FSP(LLL),SSP(LLL),
     1            ((DEL(L),DTA(L),FRA(L)),L=1,2)
      PRINT 2003, NAM(KKK),NAM(LLL)
      PRINT 2001, NAM(KKK),TCP(KKK),TSP(KKK),
     1            ((FCP(I,KKK),SCP(I,KKK)),I=1,4)
      PRINT 2002
      DO 201 J=1,22
      IF (NI .EQ. 0) GO TO 290
      PRINT 2001, LAB,AGE(J),AST(J),((FCT(I,J),SCT(I,J)),I=1,4)
      GO TO 201
  290 PRINT 2001, LAB,ACT(J),AGE(J),((FCT(I,J),SCT(I,J)),I=1,4)
  201 CONTINUE
      PRINT 2002
      PRINT 2001, NAM(LLL),TCP(LLL),TSP(LLL),
     1            ((FCP(I,LLL),SCP(I,LLL)),I=1,4)
      IF ((P .EQ. PPP) .AND. (PM .EQ. PMO)) GO TO 800
      KKK=9
      P=PPP
      PM=PMO
      GO TO 100
  800 RETURN
```

```
2000 FORMAT (1H1///7X*X = XS*////7X*LOADING PATH*10XA3* -*A3/////76X*FS
    1*I1,* - FS*4X*FS*I1,* - FS*16X*FS3 - FS*4X*FS3 - FS*/7X*POINT*10X*
    2TC*10X*TS*10X*FS*10X*SS*4X*FS*I1,* - FS*4X*---------*3X*----------*4
    3X*FS3 - FS*4X*---------*3X*----------*/79X*FS*I1,2X,3X*FS*I1,* - FS*,
    4I1,19X*FS*I1,5X*FS3 - FS*I1///)
2001 FORMAT (7X,A3,2X,2F12.2,8F12.4)
2002 FORMAT (/)
2003 FORMAT (1H1///7X*LOADING PATH*10XA3* -*A3/////49X*X = XTOP*17X*X =
    1 0*19X*X = XS*17X*X = XBOT*//7X*POINT*10X*TC*10X*TS*4(10X*FC*10X*S
    2C*)////)
     END


      SUBROUTINE PRECS (SC,FC)
C
C     CONCRETE STRAIN FOR SPECIFIED VALUES OF X
C
      COMMON / CONST / A1,A2,A3,B1,B2,B3,B4,C1,D1,D2,D3,D4,E1,E2,E3,E4,
     1                 NSUST,NSUCO,NTYST,NS,AGR,NAM(10),NNN,PPP,PMO,CMI,
     2                 ALP,BS,INDEX,AGE(23),TCP(10),TSP(10),FSP(10),
     3                 SSP(10),FCP(4,10),SCP(4,10),SCC(5,4),AST(22),
     4                 ACT(22),XXX(4),XST(5),FC3(5),IJK,NI,TTK4,AS(8),NS
     5                 AME
      COMMON / COEFF / Q1,Q2,G1,G2
      DIMENSION SC(1),FC(1)
      DO 100 I=1,5
      FC(I)=G1+G2*XST(I)
  100 SC(I)=Q1+Q2*FC(I)
      RETURN
      END


      SUBROUTINE   SURST   (FF,SS,TA,TB)
C
C     STRESS-STRAIN-TIME SURFACE OF PRESTRESSING STRANDS
C
      COMMON / CONST / B1,B2,B3,A1,A2,A3,A4,TEM(230)
      DATA MFF,MSS / 3HFFF,3HSSS /
      ENTRY FFF
  100 MMM=MFF
      IF ((SS.LT.0.3).OR.(SS.GT.0.9)) GO TO 501
      IF (TA.EQ.0.00) GO TO 101
      IF (TA.LT.0.01) GO TO 502
      TT=ALOG10(TA+1.0)
      FF=B1+SS*(B2-A1-A2*TT+SS*(B3-A3-A4*TT))
      IF ((FF.LT.0.3).OR.(FF.GT.0.9)) GO TO 506
      RETURN
  101 FF=B1+SS*(B2+SS*B3)
      IF ((FF.LT.0.3).OR.(FF.GT.0.9)) GO TO 506
      RETURN
      ENTRY SSS
  200 MMM=MSS
      IF ((FF.LT.0.3).OR.(FF.GT.0.9)) GO TO 500
      IF (TA.EQ.0.00) GO TO 201
      IF (TA.LT.0.01) GO TO 502
      TT=ALOG10(TA+1.0)
```

```
      CA=A3+A4*TT-B3
      CB=A1+A2*TT-B2
      CC=FF-B1
      CD=CB*CB-4.0*CA*CC
      IF (CD.LT.0.0) GO TO 503
      SS=-0.5*(CB+SQRT(CD))/CA
      IF ((SS.LT.0.3).OR.(SS.GT.0.9)) GO TO 507
      RETURN
  201 CD=B2*B2-4.0*B3*(B1-FF)
      IF (CD.LT.0.0) GO TO 503
      SS=0.5*(SQRT(CD)-B2)/B3
      IF ((SS.LT.0.3).OR.(SS.GT.0.9)) GO TO 507
      RETURN
  500 PRINT 2000, MMM,FF                  $          GO TO 600
  501 PRINT 2001, MMM,SS                  $          GO TO 600
  502 PRINT 2002, MMM,TA                  $          GO TO 600
  503 PRINT 2003, MMM,FF,TA               $          GO TO 600
  506 PRINT 2006, MMM,SS,TA,FF            $          GO TO 600
  507 PRINT 2007, MMM,FF,TA,SS            $          GO TO 600
  600 CALL EXIT
 2000 FORMAT (8(/),10X*SUBROUTINE*5X,A3///10X*INADMISSIBLE STRESS INPUT
     1VALUE*9X*F  =*F14.4)
 2001 FORMAT (8(/),10X*SUBROUTINE*5X,A3///10X*INADMISSIBLE STRAIN INPUT
     1VALUE*9X*S  =*F14.4)
 2002 FORMAT (8(/),10X*SUBROUTINE*5X,A3///10X*INADMISSIBLE TIME INPUT VA
     1LUE*11X*T  =*F14.4)
 2003 FORMAT (8(/),10X*SUBROUTINE*5X,A3///10X*INADMISSIBLE COMBINATION O
     1F INPUT VALUES*9X*F  =*F14.4//59X*T  =*F14.4)
 2006 FORMAT (8(/),10X*SUBROUTINE*5X,A3///10X*INADMISSIBLE COMBINATION O
     1F INPUT VALUES*9X*S  =*F14.4//59X*T  =*F14.4////59X*F  =*F14.4)
 2007 FORMAT (8(/),10X*SUBROUTINE*5X,A3///10X*INADMISSIBLE COMBINATION O
     1F INPUT VALUES*9X*F  =*F14.4//59X*T  =*F14.4////59X*S  =*F14.4)
      END
```

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