Prestress Losses in Partially Prestressed High Strength Concrete Beams

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The results of a comprehensive parametric study on prestress losses in prestressed and partially prestressed high strength concrete beams are reported. Attention is focused on the influence of the partial prestressing ratio (from no prestressing to full prestressing) and the compressive strength of concrete, from 6 ksi (41 MPa) up to 10 ksi (69 MPa). Different beam cross sections, representing building and bridge girders with various spans and spacings, were studied. Additional parameters investigated include the strength and type of prestressing steel (stress-relieved or low-relaxation), the yield strength of reinforcing steel, the relative humidity of the environment and curing conditions (steam- or moist-curing). Time-dependent prestress losses were computed through an accurate time-step analysis procedure, which was implemented in a computer program. Conclusions and recommendations are drawn for use in design practice. The results are applicable to pretensioned as well as post-tensioned members. Proposed design recommendations are suggested to replace current lump sum design tables suggested in the AASHTO Specifications and the ACI 343R-88 report on analysis and design of reinforced concrete bridge structures.

The prestressing force initially applied to a concrete member decreases with time due to several sources of losses. In pretensioned members, these sources include elastic shortening, creep of concrete, shrinkage of concrete and relaxation of the prestressing steel. For post-tensioned members, losses due to friction and anchorage set are also added. Elastic shortening, friction and anchorage set losses are instantaneous, while steel relaxation, concrete creep and shrinkage losses are time-dependent.

The difference between the initial stress in the prestressing steel and the stress at any time, t, is defined as the total prestress loss, TPL, at time t. The

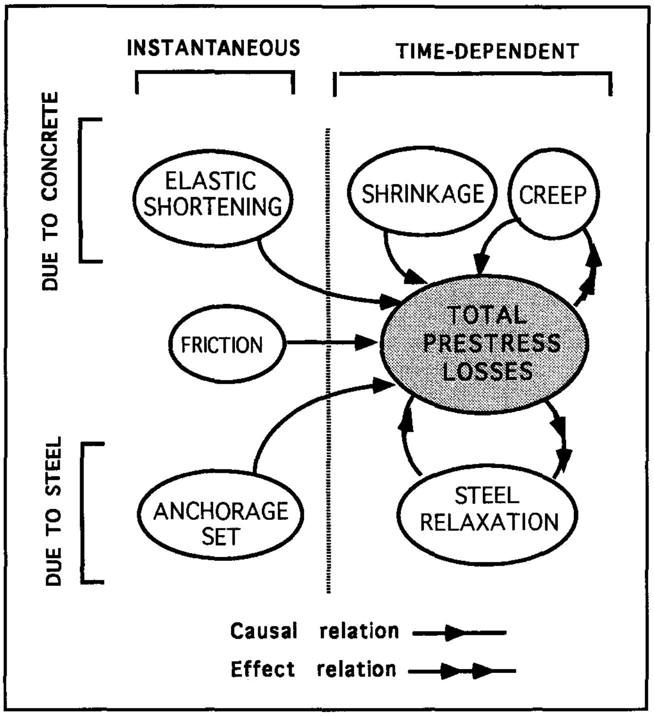

Fig. 1. Interrelationships of causes and effects between prestress losses.

TPL is also used to describe the total loss expected at the end of the life of the structure and is applied as a safe value in design. In this study, the total prestress loss does not account for the effects of friction and anchorage sets which are particular to post-tensioned structures. The magnitude of the TPL has little effect on the ultimate flexural strength of a prestressed concrete member. However, an error in the estimate of this loss could result in a false prediction of the behavior of the member under service loads, and may cause significant error in computations of stresses, cracking moments and crack widths, and camber or deflection.

Numerous studies have been conducted in the past to evaluate prestress losses.[1-13] However, most of these studies addressed fully prestressed concrete members made from normal strength concretes, and normal, stress-relieved strand. The main objective of this investigation is to provide a preliminary evaluation of prestress losses for high strength, partially prestressed concrete members. The two main parameters are the partial prestressing ratio, PPR, ranging from 0 to 1.0, and the concrete compressive strength, f'_c, ranging from 6 to 10 ksi (41 to 69 MPa).

The partial prestressing ratio, PPR, describes the relative contribution of the prestressing steel and the reinforcing steel to the resistance of the section. Its numerical value is defined further in Eq. (16). A partially prestressed beam is defined here as a beam containing a combination of reinforcing bars and prestressing tendons to resist bending. A fully prestressed beam is assumed without (or with a negligible amount of) reinforcing bars.

This limited study was carried out as part of NCHRP Project 12-33, on the development of a comprehensive bridge design code. Its final objective was to update the lump sum estimates of prestress losses currently given in the AASHTO Specifications[14] and in ACI Report 343R-88.[15]

METHODS FOR ESTIMATING PRESTRESS LOSSES

The estimation of prestress losses may be carried out at several different levels. In common practical design cases, the detailed calculation of losses is not necessary, and a lump sum estimate may be sufficient. For cases in which greater accuracy is required, it may be necessary to estimate separate (shrinkage, creep, etc.) losses, with due account to member geometry, material properties, environmental conditions and construction method. Increased accuracy may be still further achieved by accounting for the interdependence of time-dependent losses, using discrete time intervals. This procedure is generally called the time-step (T-S) method.

Many methods and design recommendations have been developed to predict prestress losses.[1-13] For design purposes, they can be classified according to three levels of difficulty and related computational accuracy, namely:

1. Lump sum estimate of total prestress losses, TPL

2. Lump sum estimates of the separate prestress losses due to a particular effect, such as shrinkage, creep, or relaxation

3. Accurate determination of cumulative losses by the time-step (T-S) method

Lump Sum Estimate of Total Prestress Losses

As early as 1958, ACI-ASCE Joint Committee 423[1] recognized the need for approximate expressions to estimate prestress losses in design. The values of 35 ksi (241 MPa) for pretensioned members and 25 ksi (172 MPa) for post-tensioned members were recommended for lump sum losses. These values included losses due to elastic shortening, steel relaxation, and shrinkage and creep of concrete, but excluded losses due to friction and anchorage set.

The same lump sum estimate of total prestress losses were included in the AASHTO Specifications[14] for highway bridges. These loss values were based on use of normal strength concrete, normal stress-relieved strand, normal prestress levels (i.e., concrete and steel stresses within code allowable) and average environmental exposure conditions; they include elastic shortening losses, as well as the time-dependent losses, TDL, due to shrinkage, creep and relaxation.

Note that some adjustments to these values were suggested in several investigations, such as by Hernandez and Gamble[5] and Zia, et al.[9] They were later modified to reflect the effect of compressive strength and type of prestressing steel, as recommended in ACI Report 343R-88[15] (Table 9.6.4.1), reproduced in Table A1 of Appendix A.

Lump Sum Estimate of Separate Prestress Losses

Several methods can be found in the technical literature to estimate the separate contribution of each source of prestress losses.[7,10,12,14,15] The total prestress loss is then obtained by summing up the separate contributions. Many of these methods have merit and can be used. The AASHTO Specifications[14] and ACI-ASCE Committee 343 report[15] provide equations to calculate each separate prestress loss depending on its source. Such prediction equations require some basic information on material properties and environmental conditions, but they are reasonably easy to implement.

Accurate Determination of Prestress Losses: Time-Step Method

The time-step (T-S) method is the most accurate technique to determine time-dependent losses (TDL) due to steel relaxation, creep and shrinkage of concrete. However, it also requires accurate information on the time-dependent material properties, such as creep and shrinkage strains. In order to fully understand the T-S method, it is essential to realize that time-dependent losses are also interdependent.

Fig. 1 provides an overall diagram of how total losses are cumulative and illustrates the interrelational causes and effects between the different sources of prestress losses. It can be observed, for instance, that relaxation reduces the stress in the steel, which in turn reduces the stress in the concrete. Thus, creep loss, being dependent on the stress in the concrete adjacent to the steel, tends to get reduced as well, leading to a reduced rate of loss in steel relaxation.

To account for changes in the various effects with time, a step-by-step procedure is used with various time intervals such as given, for instance, in Table 1. The beginning of a time interval can be selected to correspond to a particular milestone during construction. The stress in the steel at the beginning of any time interval is taken equal to that at the end of the preceding interval and is utilized to compute incremental losses during the given interval. The T-S procedure allows for an accurate computation of prestress losses for various time intervals, and the resulting cumulative total prestress loss at the end of the life of the member. Details of the analytical procedure for the T-S method can be found in Refs. 6, 16 and 17.

CALCULATION OF PRESTRESS LOSSES

The main equations used in this study for the calculation of prestress losses due to elastic shortening, relaxation of prestressing steel, shrinkage of concrete and creep of concrete, by the time-step (T-S) method,[16] are summarized next.

Elastic Shortening

The loss in the prestressing steel stress due to elastic shortening is expressed as:

$$\Delta f_{pES} = \frac{\left(f_{cgs}\right)_{F_J}\left[f_{pJ} - \Delta f_{pR}(t_0, t_t)\right] + \left(f_{cgs}\right)_G f_{pJ}}{\left(f_{pJ} / n_{pi}\right) + \left(f_{cgs}\right)_{F_J}} \quad (1)$$

where

$(f_{cgs})_{F_J}$ = stress in concrete at centroid of prestressing steel due to the force F_J:

$$\left(f_{cgs}\right)_{F_J} = \frac{F_J}{A_c} + \frac{F_J e_o^2}{I} \quad (2)$$

in which

F_J = prestressing force at end of jacking

Table 1. Recommended minimum time intervals.[16]

Step	Beginning time, t_i (day)	End time, t_j (day)
1	Release of prestressing steel	Age = 1
2	End of Step 1 = 1	Age = 7
3	End of Step 2 = 7	Age = 30
4	End of Step 3 = 30	Age = 90
5	End of Step 4 = 90	Age = 365
6	End of Step 5 = 365	Age = 1825 (5 years)
7	End of Step 6 = 1825	Age = 14,600 (40 years)

A_c = transformed area of concrete at section considered

e_o = prestressing force eccentricity at section considered

$(f_{cgs})_G$ = stress in concrete at centroid of prestressing steel due to self weight of member:

$$\left(f_{cgs}\right)_G = -\frac{M_G e_o}{I} \quad (3)$$

in which

M_G = moment due to self weight of member

I = transformed moment of inertia of section considered

f_{pJ} = stress in prestressing steel at end of jacking

n_{pi} = initial modular ratio = E_{ps}/E_{ci}

$\Delta f_{pR}(t_0,t_t)$ = relaxation loss of prestressing steel stress during the time interval (t_0,t_t), i.e., time of stressing to time of transfer [see Eq. (4)]

Note that, while Eq. (1) is more accurate than the usual equation used in the AASHTO Specifications,[14] both equations give close numerical values. The transformed moment of inertia should include the contribution of non-prestressed reinforcement. However, for pretensioned members, the transformed moment of inertia can be replaced, as a first approximation, by the gross moment of inertia.

Relaxation of Steel

The loss in the prestressing steel stress (i.e., the change in stress) due to relaxation of steel over time interval (t_i,t_j) is expressed as:

$$\Delta f_{pR}\left(t_i, t_j\right) = \frac{f_{ps}(t_i)}{10}\left(\frac{f_{ps}(t_i)}{f_{py}} - 0.55\right)\log\left(\frac{t_j}{t_i}\right) \quad (4)$$

where

$f_{ps}(t_i)$ = stress in prestressing steel at time t_i at section considered

f_{py} = yield strength of prestressing steel

t_i,t_j = respectively, the beginning and end of a time interval; the ratio t_j/t_i should be ≥ 1

This equation applies provided $f_{ps}(t_i)$ is larger than 0.55 f_{py}. Note that the divisor 10 in Eq. (4) applies to stress-relieved steel and is replaced by 45 for low-relaxation steel.

Shrinkage of Concrete

The loss in the prestressing steel stress due to shrinkage of concrete over a time interval (t_i, t_j) is expressed as:

$$\Delta f_{pS}(t_i, t_j) = E_{ps} \varepsilon_{SU} K_{SH} K_{SS} \frac{b(t_j - t_i)}{(b + t_i)(b + t_j)} \quad (5)$$

where

E_{ps} = modulus of elasticity of prestressing steel
ε_{SU} = ultimate shrinkage strain of concrete material
K_{SH} = correction factor for shrinkage due to relative humidity:

$$K_{SH} = 1.4 - 0.01\,H \quad (6)$$

H = relative humidity in percent
K_{SS} = shape and size factor for shrinkage:

$$K_{SS} = 1.14 - 0.09 \frac{V}{S} \quad (7)$$

in which

$\frac{V}{S}$ = volume to surface ratio of member
b = parameter; equals 35 for moist-cured concrete and 55 for steam-cured concrete

Creep of Concrete

The stress loss in the prestressing steel due to creep of concrete over a time interval (t_i, t_j) is expressed as:

$$\Delta f_{pC}(t_i, t_j) = n_p\, C_{CU}\, K_{CH}\, K_{CA}\, K_{CS}\, f_{cgs}(t_i)\, [g(t_j) - g(t_i)] \quad (8)$$

where

n_p = modular ratio = E_{ps}/E_c
C_{CU} = ultimate creep coefficient of concrete material
K_{CH} = correction factor of humidity for creep for both moist- and steam-cured concrete:

$$K_{CH} = 1.27 - 0.0067\,H \quad (9)$$

K_{CA} = age at loading factor for creep

For moist-cured concrete:

$$K_{CA} = 1.25\, t_A^{-0.118} \quad (10)$$

For steam-cured concrete:

$$K_{CA} = 1.13\, t_A^{-0.095} \quad (11)$$

t_A = age at loading in days
K_{CS} = shape and size factor for creep:

$$K_{CS} = 1.14 - 0.09 \frac{V}{S} \quad (12)$$

in which

$\frac{V}{S}$ = volume to surface ratio of member

$f_{cgs}(t_i)$ = stress in concrete at centroid of prestressing steel at time t_i due to prestressing force and dead load:

$$f_{cgs}(t_i) = \frac{\left[f_{ps(t_i)}\right] A_{ps}}{A_c} \left(1 + \frac{e_o^2}{r^2}\right) - \frac{M_D e_o}{I} \quad (13)$$

in which

A_{ps} = area of prestressing steel in tension zone
M_D = moment due to dead load
r = radius of gyration of cross section

$$g(t_j) = \text{time function} = \frac{t_j^{0.6}}{\left(10 + t_j^{0.6}\right)} \quad (14)$$

$$g(t_i) = \text{time function} = \frac{t_i^{0.6}}{\left(10 + t_i^{0.6}\right)} \quad (15)$$

Justification for Eqs. (10), (11), (14) and (15) can be found in Ref. 18. In the parametric evaluation of this study, only two values of n_p were used, one corresponding to the modulus E_{ci} at time of release, and one corresponding to E_c at 28 days. It should be noted that basic creep equations different from Eqs. (8), (14) and (15) have been recently developed by Bažant and Kim[19] and could have been used in this study. However, the authors believe that the main results and conclusions of this study would not be altered.

DESIGN PROCEDURE AND COMPUTER IMPLEMENTATION

The design of the partially prestressed concrete beams for which losses were calculated in this investigation was carried out using the partial prestressing ratio (PPR) method described by Naaman and Siriaksorn.[20] The PPR is defined as the ratio of moment resistance taken by the prestressing steel to the moment resistance taken by the total steel; as a first approximation, it can be taken as the ratio of forces instead of moments [see Eq. (16)].

The design starts with a selected value of the PPR, which is then used to solve the flexural strength equations at nominal bending resistance and to determine the required areas of tension reinforcing steel, A_s, and prestressing steel, A_{ps}. This was followed by a service load analysis to check that crack width, deflection and fatigue criteria were all satisfactory. For preliminary design of the cross section, the final prestressing force was assumed to be equal to 83 percent of the initial prestressing force. This is equivalent to an estimate of the total prestress loss of about 17 percent.

Three small computer programs were developed for use in the parametric studies. The first program was used to calculate the live load moment for simple span bridges according to the AASHTO Specifications.[14] The second program was used to calculate the required areas of prestressing steel, A_{ps}, and reinforcing steel, A_s, by the partial prestressing ratio (PPR) approach,[20] using the ultimate strength design method according to the ACI Building Code.[21]

The third program was developed to compute prestress losses by the time-step (T-S) method. This program can accommodate both prestressed and partially prestressed concrete members. In this program, the steel relaxation was calculated based on the steel stress at the beginning of each time interval selected. The concrete creep strain at any time, t, was calculated on the basis of the elastic strains induced by the forces and bending moments applied in the previous intervals. Finally, the concrete shrinkage strain was computed as the total shrinkage occurring from the time of release of prestress to the time considered.

Table 2. List of parameters for Study I.

No.	Group	Parameter	Values
1	Material strength	Compressive strength of concrete, f'_c (ksi) Tensile strength of prestressing steel, f_{pu} (ksi) Yield strength of reinforcing steel, f_y (ksi)	6, 8, 10 145, 235, 270 40, 60, 75
2	Environmental condition	Curing condition of concrete Relaxation type of prestressing steel Relative humidity, H (percent)	Steam and moist Normal and low 40, 60, 80, 100
3	Design variable	Partial prestressing ratio, PPR	0.2, 0.4, 0.6, 0.8, 1.0

Note: Initial stress in the prestressing steel, $f_{pi} = 0.70\, f_{pu}$.
Design data: PCI beam 12RB28.[23]

Table 3. List of parameters for Studies II-V.

		Values			
Group	**Parameter**	**Study II I-girder**	**Study III Box girder**	**Study IV Hollow-core slab**	**Study V Double-tee beam**
Material strength	f'_c (ksi) f_{pu} (ksi)	6, 8, 10 145, 235, 270	6, 8, 10 145, 235, 270	6, 8, 10 270	6, 8, 10 270
Design variables	Section	IV-I girder	B IV-36 girder	4HC8 4HC10 4HC12	8DT16 8DT20 8DT24
	L (ft)	60, 70, 80	50, 60, 70	20, 25, 30, 35, 40	20, 30, 40, 50, 60
	S (ft)	5, 6, 7, 8	5, 6, 7	4	8
	PPR	0.2, 0.4, 0.6, 0.8, 1.0	0.2, 0.4, 0.6, 0.8, 1.0	1.0	1.0

Note: Reference base: moist-cured concrete; normal steel relaxation; H = 40 percent; f_y = 60 ksi.

PARAMETRIC EVALUATION — STUDIES I TO V

An extensive parametric evaluation of prestress losses in high strength, prestressed and partially prestressed concrete members was undertaken using the three computer programs. Parameters and variables included the type of beam cross section, the partial prestressing ratio, PPR, the concrete compressive strength, f'_c, the strength and the type of prestressing steel, environmental conditions, and the strength and grade of the reinforcing steel. Details are given in Ref. 22.

Five separate parametric studies, numbered I to V, were carried out. The numerical values of design parameters used are listed in Tables 2 and 3. Studies II and III were selected to represent bridge members, while Studies IV and V represented building members.

Table 4. Properties of concrete used in the parametric studies.

Concrete compressive strength, f'_c (ksi)	6	8	10
Concrete compressive strength at time of initial prestress, f'_{ci} (ksi)	4.800	6.400	8.000
Ultimate creep coefficient, C_{CU}	2.4	2.0	1.6
Shrinkage strain for moist-cured concrete, ε_{SU}	0.0006	0.0006	0.0006
Age at loading for moist-cured concrete, t_A (day)	7	7	7
Shrinkage strain for steam-cured concrete, ε_{SU}	0.0004	0.0004	0.0004
Age at loading for steam-cured concrete, t_A (day)	1	1	1

Note: Elastic modulus of concrete: $E_c = 57{,}000\sqrt{f'_c}$, in psi.

In Study I, all parameters were systematically investigated. For example, the relative humidity was varied from 40 to 100 percent, while for the other studies it was kept constant at 40 percent. Although slabs are shown in the figures for Studies I, II and III, the slabs were used only to determine the beam dead and live loads for a given beam spacing; thus, composite action was not considered. These studies are briefly described.

Study I: Rectangular Beam

Study I dealt with the evaluation of prestress losses for a typical partially prestressed concrete rectangular beam. The beam spacing was assumed to be 6 ft (1.8 m) and the dead load, including the beam's own weight, was taken as 1 kip per linear ft (1488 kg/m). The live load was taken as 0.6 kips per linear ft (893 kg/m). Here, all the parameters which affect prestress losses were systematically investigated.

The parameters were divided into three groups, namely: material strength variables, environmental conditions and design variables (see Table 2). Table 4 provides some information on the properties of concretes used in this study.

The results of Study I are summarized in Table 5, Fig. 2 and Fig. 3. Table 5 includes the main results of time-dependent losses, TDL, and elastic shortening covering all the parameters investigated, while Fig. 2 shows the variation of TDL with time for different PPR levels. Fig. 3 shows the upper and lower limits of TDL. The upper and lower limits ranged from 22 to 32 ksi (152 to 221 MPa) when high strength wires and strands were used.

Table 5. Prestress losses for simply supported partially prestressed rectangular beam for Study I.

		PPR = 0.20			PPR = 0.40			PPR = 0.60			PPR = 0.80			PPR = 1.00		
Parameter	**Values**	**TDL (ksi)**	**TIL (ksi)**	**TPL (ksi)**	**TDL (ksi)**	**TIL (ksi)**	**TPL (ksi)**	**TDL (ksi)**	**TIL (ksi)**	**TPL (ksi)**	**TDL (ksi)**	**TIL (ksi)**	**TPL (ksi)**	**TDL (ksi)**	**TIL (ksi)**	**TPL (ksi)**
Concrete	6	21.7	0.0	22.0	24.0	3.0	27.0	26.3	5.9	32.2	28.8	9.0	37.8	31.5	12.3	43.7
strength	8	23.3	0.1	23.5	24.4	2.5	26.9	26.0	4.8	30.8	27.6	7.3	34.9	29.3	10.0	39.4
f'_c (ksi)	10	24.2	0.1	24.2	25.0	2.0	27.1	26.0	4.1	30.1	27.0	6.3	33.3	28.1	8.7	36.8
Prestressing	145	16.9	0.1	17.1	18.4	2.4	20.8	19.9	4.8	24.7	21.4	7.3	28.7	23.0	9.9	32.9
steel strength	235	23.3	0.1	23.5	24.4	2.5	26.9	26.0	4.8	30.8	27.6	7.3	34.9	29.3	10.0	39.4
f_{pu} (ksi)	270	25.3	0.1	25.4	26.6	2.3	28.9	28.1	4.6	32.7	29.7	7.1	36.8	31.4	9.7	41.1
Reinforcing	40	23.1	0.1	23.2	24.5	2.4	26.9	26.0	4.8	30.8	27.6	7.3	34.9	29.3	10.0	39.4
steel strength	60	23.3	0.1	23.5	24.4	2.5	26.9	26.0	4.8	30.8	27.6	7.3	34.9	29.3	10.0	39.4
f_y (ksi)	75	23.1	0.1	23.2	24.5	2.4	26.9	26.0	4.8	30.8	27.6	7.3	34.9	29.3	10.0	39.4
Curing	Steam	20.1	0.1	20.2	21.4	2.4	23.8	22.8	4.8	27.6	24.3	7.3	31.6	25.9	10.0	35.9
condition	Moist	23.3	0.1	23.5	24.4	2.5	26.9	26.0	4.8	30.8	27.6	7.3	34.9	29.3	10.0	39.4
Type of	Normal	23.3	0.1	23.5	24.4	2.5	26.9	26.0	4.8	30.8	27.6	7.3	34.9	29.3	10.0	39.4
relaxation	Low	12.0	0.2	12.2	14.3	2.5	16.8	16.7	4.9	21.7	19.3	7.5	26.8	21.9	10.3	32.2
Relative	40	23.3	0.1	23.5	24.4	2.5	26.9	26.0	4.8	30.8	27.6	7.3	34.9	29.3	10.0	39.4
humidity	60	21.6	0.1	21.7	22.7	2.4	25.1	23.9	4.8	28.7	25.2	7.3	32.5	26.6	10.0	36.6
H (percent)	80	20.1	0.1	20.2	20.9	2.4	23.3	21.8	4.8	26.6	22.8	7.3	30.1	23.9	10.0	33.9
	100	14.5	0.1	14.6	15.1	2.4	17.4	15.7	4.8	20.4	16.4	7.3	23.7	17.1	10.0	27.1

Notes:

1. Design data: 12RB28 PCI beam; building structure; and ACI Building Code (ACI 318-89).
2. Reference base: moist-cured concrete; normal relaxation steel; f_y = 60 ksi; f_{pu} = 235 ksi; f'_c = 8 ksi; and H = 40 percent.
3. TDL = Time-Dependent Losses = Creep of Concrete + Shrinkage of Concrete + Relaxation of Steel.
4. TIL = Time-Independent Losses = Elastic Shortening.
5. Total Prestress Losses, TPL = TDL + TIL.

Study II: AASHTO I Girder

The main objective of Study II was to evaluate prestress losses for a partially prestressed concrete bridge I-girder. A Type IV AASHTO girder was chosen. Three different spans, namely 60, 70 and 80 ft (18, 21 and 24 m), and corresponding spacings of 6, 7 and 8 ft (1.8, 2.1 and 2.4 m) (i.e., 10 percent of the span), were used in the evaluation. For each span, five values (0.2, 0.4, 0.6, 0.8 and 1.0) of PPR, and three values of f'_c (6, 8 and 10 ksi) (41, 55 and 69 MPa) were examined, as given in Table 3. Live loads corresponding to AASHTO HS-20 truck loading were used.

The results of Study II are summarized in Table 6; note that for the last line of the table, a constant beam spacing of 5 ft (1.5 m) was used, instead of 8 ft (2.4 m), to illustrate the effects of reduced beam spacing and full prestressing. Fig. 4 shows the upper and lower limits of TDL for this study. The upper and lower limits ranged from 25 to 41 ksi (186 to 276 MPa) when wires and strands were used.

Study III: AASHTO Box Girder

The main objective of Study III was to evaluate prestress losses for a partially prestressed concrete bridge box girder. A Type IV-36 AASHTO box girder was considered. Three different spans, namely, 50, 60 and 70 ft (15, 18 and 21 m), and three different spacings, namely, 5, 6 and 7 ft (1.5, 1.8 and 2.1 m), were used in the evaluation. The corresponding values of dead load were, respectively, 1.3, 1.5 and 1.7 kips per linear ft (1934, 2232 and 2530 kg/m), including the beam's own weight, while the live load was the AASHTO HS-20 truck loading.

For each span, five values (0.2, 0.4, 0.6, 0.8 and 1.0) of PPR, and three values of f'_c (6, 8 and 10 ksi) (41, 55 and 69 MPa) were examined as given in Table 3. The volume to surface ratio of these beams present in shrinkage and creep computations included the internal surface of the box.

The results of Study III are summarized in Table 7 while Fig. 5 shows the upper and lower limits of TDL for this study. The upper and lower limits ranged from about 20 to 24 ksi (138 to 165 MPa) when wires and strands were used.

Study IV: Hollow-Core Slabs

The main objective of Study IV was to evaluate prestress losses for fully prestressed hollow-core slabs. The hollow-core slabs considered were 4HC8, 4HC10 and 4HC12 as described in the PCI Design Handbook.[23] The values of dead load were taken as 0.325, 0.37 and 0.375 kips per linear ft (484, 551 and 558 kg/m), respectively; the corresponding live load was taken as 0.4 kips per linear ft (595 kg/m).

For each slab, three practical spans were selected. The main parameters were the type of cross section and the compressive strength of concrete as given in Table 3.

The results of Study IV are summarized in Table 8. Fig. 6 shows the upper and lower limits of TDL for this study. The upper and lower limits ranged from 33 to 43 ksi (227 to 296 MPa) when wires and strands were used.

Study V: Double-Tee Beams

The main objective of Study V was to evaluate prestress losses for fully prestressed double-tee beams. The double-tee beams were 8DT16, 8DT20, and 8DT24 as given in the

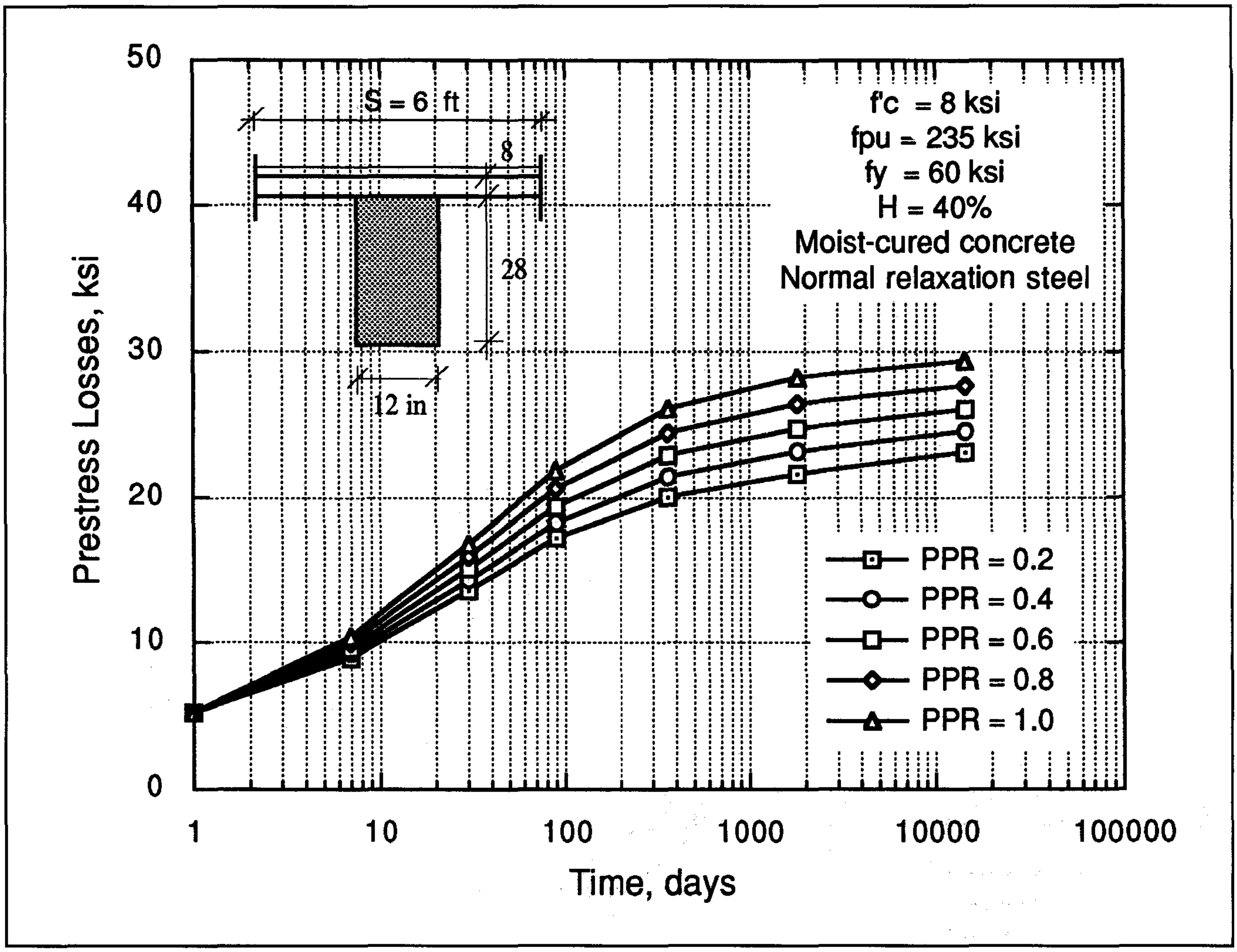

Fig. 2. Typical variation of time-dependent prestress losses with time and level of prestress.

PCI Design Handbook,[23] and for each beam, three practical spans were considered.

The main parameters were the type of cross section and the compressive strength of concrete as given in Table 3. The dead load considered was 0.54, 0.56 and 0.62 kips per linear ft (804, 833 and 923 kg/m), respectively, and included the weight of a 2 in. (51 mm) topping. The live load was taken as 0.8 kips per linear ft (1190 kg/m).

The results of Study V are summarized in Table 9. Fig. 7 shows the upper and lower limits of TDL for this study. The upper and lower limits ranged from 34 to 47 ksi (234 to 324 MPa) when wires and strands were used.

RECOMMENDATIONS FOR DESIGN

The lump sum estimates of time-dependent prestress losses given in Tables 5 to 9 reflect values and trends obtained from a computerized time-step analysis of a large number of bridge and building members designed for a common range of variables with particular attention to the concrete compressive strength ranging from 6 to 10 ksi (41 to 69 MPa), the partial prestressing ratio, PPR, ranging from 0.2 to 1, and the shape of the section.

An analysis of the data of Tables 5 to 9 led to approximate predictions of upper bound and average lump sum values of time-dependent prestress losses (i.e., creep, shrinkage and relaxation) for the various types of beams studied. These lump sum estimates are summarized in Table 10. They are applicable to prestressed and partially prestressed concrete flexural members made from normal weight concrete with up to 10 ksi (69 MPa) compressive strength, and using either prestressing bars, wires or strands with normal (stress-relieved) or low-relaxation properties.

The upper bound is recommended when an adverse combination of parameters exists, such as low concrete compressive strength, low relative humidity and moist-curing conditions. For members prestressed with bars, the difference between the average and the upper bound was found insignificant to justify a different expression. For box girders, I-girders and solid rectangular beams, the effect of concrete compressive strength up to 10 ksi (69 MPa) was found to be relatively negligible.

The approximate values of time-dependent losses given in Table 10 may be used for:

- Post-tensioned, non-segmental members with spans up to 150 ft (46 m), stressed at concrete age of 10 to 30 days.
- Pretensioned members constructed of normal weight concrete stressed after attaining a concrete compressive strength f'_{ci} = 3500 psi (24 MPa).

For members made from structural lightweight concrete,

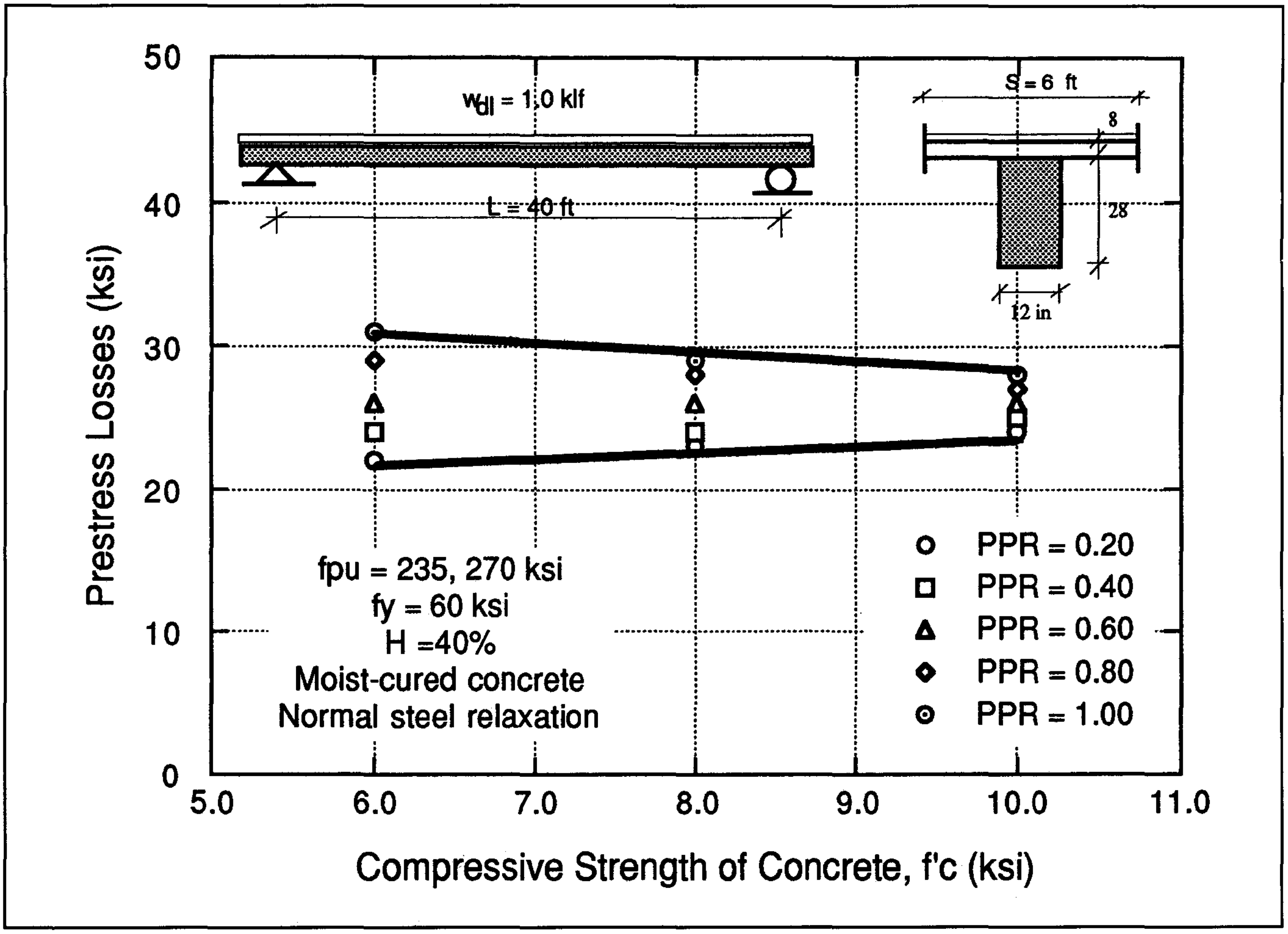

Fig. 3. Upper and lower limits of time-dependent losses for Study I.

with unit weight in the range of 115 to 120 lb per cu ft (1840 to 1920 kg/m³), it is recommended to increase the values given in Table 10 by 5 ksi (34 MPa). Although lightweight concrete was not included in the parameters of this study, this recommendation is based on a recommendation made by Zia, et al.[9]

For low-relaxation strands, reduce the values recommended in Table 10, respectively, by 4 ksi (28 MPa) for box girders, 6 ksi (41 MPa) for rectangular beams and I-girders, and 8 ksi (55 MPa) for single tees, double tees, and hollow-core slabs.

The partial prestressing ratio, PPR, used in Table 10, can be computed, as a first approximation, from:

$$\text{PPR} = \frac{A_{ps} f_{py}}{A_{ps} f_{py} + A_s f_y} \qquad (16)$$

where A_{ps} and A_s are cross-sectional areas of the prestressing steel and the tensile reinforcing steel, respectively, and f_{py} and f_y are their corresponding yield strengths. Thus, a fully prestressed beam would have $A_s = 0$ and PPR = 1.

Table 10 provides different equations for different concrete beam sections. In the absence of specific information on the type of cross section used, the following estimate of average time-dependent losses, TDL, as a function of the concrete compressive strength, f'_c, and the partial prestressing ratio, PPR, is recommended for design:

In US units:

$$\text{TDL} = 33\left(1 - 0.15\frac{f'_c - 6}{6}\right) + 6\ \text{PPR} \qquad \text{(ksi)} \qquad (17a)$$

In SI units:

$$\text{TDL} = 231\left(1 - 0.15\frac{f'_c - 42}{42}\right) + 42\ \text{PPR} \qquad \text{(MPa)} \qquad (17b)$$

As a first approximation and for the purpose of using Eq. (17) only, the partial prestressing ratio, PPR, can be estimated from Eq. (16).

For members made from structural lightweight concrete, it is recommended to increase the values predicted from Eq. (17) by 5 ksi (34 MPa). For low-relaxation wires and strands, it is recommended to reduce the values predicted from Eq. (17) by 6 ksi (41 MPa).

Table 10 is recommended as a replacement of the related tables on lump sum estimate of prestress losses found in the AASHTO Specifications[14] and in the ACI Report 343-R88,[15] which is reproduced in Appendix A. The values given in Table 10 are recommended only when satisfactory previous application to the general type of structure and construction method contemplated for use has been checked.

For other types of structures or for unusual exposure conditions, more accurate estimates of time-dependent losses should be obtained. Moreover, the limitations and discus-

Table 6. Prestress losses for simply supported partially prestressed pretensioned bridge I-girders for Study II.

Span L (ft)	PPR	$f'_c = 6$ ksi									$f'_c = 8$ ksi									$f'_c = 10$ ksi								
		$f_{pu} = 145$ ksi			$f_{pu} = 235$ ksi			$f_{pu} = 270$ ksi			$f_{pu} = 145$ ksi			$f_{pu} = 235$ ksi			$f_{pu} = 270$ ksi			$f_{pu} = 145$ ksi			$f_{pu} = 235$ ksi			$f_{pu} = 270$ ksi		
		TIL (ksi)	TDL (ksi)	TPL (ksi)	TIL (ksi)	TDL (ksi)	TPL (ksi)	TIL (ksi)	TDL (ksi)	TPL (ksi)	TIL (ksi)	TDL (ksi)	TPL (ksi)	TIL (ksi)	TDL (ksi)	TPL (ksi)	TIL (ksi)	TDL (ksi)	TPL (ksi)	TIL (ksi)	TDL (ksi)	TPL (ksi)	TIL (ksi)	TDL (ksi)	TPL (ksi)	TIL (ksi)	TDL (ksi)	TPL (ksi)
60	0.20	0.2	18.4	18.6	0.2	24.9	25.1	0.2	27.2	27.4	0.1	18.8	18.9	0.1	25.2	25.3	0.1	27.6	27.7	0.0	19.1	19.1	0.0	25.5	25.5	0.0	27.9	27.9
	0.40	1.2	19.7	20.9	1.3	26.1	27.3	1.3	28.4	29.7	0.8	19.8	20.7	0.9	26.2	27.0	0.9	28.6	29.4	0.5	20.0	20.5	0.4	26.2	26.6	0.7	28.5	29.2
	0.60	2.2	21.0	23.2	2.3	27.3	29.6	2.3	29.7	32.0	1.5	20.9	22.4	1.6	27.2	28.8	1.6	29.5	31.2	1.1	20.8	21.9	0.8	26.9	27.7	1.4	29.2	30.6
	0.80	3.8	21.8	25.6	4.1	28.1	32.1	4.1	30.4	34.5	2.7	21.6	24.3	2.9	27.9	30.7	2.9	30.2	33.1	1.9	21.5	23.4	1.9	27.6	29.5	2.2	30.0	32.2
	1.00	5.4	22.6	28.0	5.9	28.8	34.7	5.9	31.2	37.1	3.9	22.2	26.1	4.1	28.5	32.7	4.2	30.9	35.1	2.8	22.1	24.9	2.9	28.4	31.3	3.0	30.8	33.7
70	0.20	0.3	18.3	18.6	0.3	24.7	25.0	0.3	27.1	27.4	0.2	18.9	19.1	0.2	25.2	25.4	0.2	27.6	27.8	0.1	18.7	18.8	0.1	25.0	25.1	0.1	27.4	27.5
	0.40	2.1	20.3	22.4	2.2	26.7	28.9	2.3	29.0	31.3	1.7	20.6	22.3	1.8	26.9	28.7	1.8	29.3	31.1	1.5	20.7	22.2	0.8	26.4	27.2	0.8	28.8	29.5
	0.60	3.9	22.4	26.2	4.2	28.6	32.8	4.2	30.9	35.2	3.1	22.3	25.4	3.4	28.6	31.9	3.4	30.9	34.3	3.0	22.7	25.7	1.5	27.7	29.2	1.5	30.1	31.6
	0.80										5.1	23.6	28.8	5.6	29.9	35.5	5.7	32.3	38.0	4.5	24.0	28.5	4.0	28.6	32.7	4.1	32.0	36.1
	1.00										7.2	25.0	32.2	7.9	31.2	39.1	8.0	33.6	41.6	6.0	25.3	31.3	6.6	29.5	36.1	6.7	33.9	40.6
80	0.20																			0.4	18.2	18.6	0.4	24.5	24.9	0.4	26.9	27.3
	0.40																			1.4	20.5	21.9	1.5	26.9	28.3	1.5	29.2	30.7
	0.60																			2.3	22.9	25.2	2.5	29.2	31.7	2.6	31.5	34.1
	0.80																											
	1.00	8.9	31.1	40.0	9.1	38.1	47.2	8.9	40.6	49.5	6.5	27.7	34.2	6.5	34.1	40.6	6.4	36.4	42.8	5.6	26.7	32.3	5.6	32.9	38.5	5.5	35.2	40.7

Notes

1. Design data: Type IV AASHTO bridge girder; four traffic lanes bridge; and HS-20 truck loading.
2. Reference base: Moist-cured concrete; normal steel relaxation; $f_y = 60$ ksi; and $H = 40$ percent.
3. TDL = Time-Dependent Losses = Creep of Concrete + Shrinkage of Concrete + Relaxation of Steel.
4. TIL = Time-Independent Losses = Elastic Shortening.
5. Total Prestress Losses, TPL = TDL + TIL.
6. The beam spacing was taken as 10 percent of the span except for the last line where the spacing was kept constant at 5 ft.

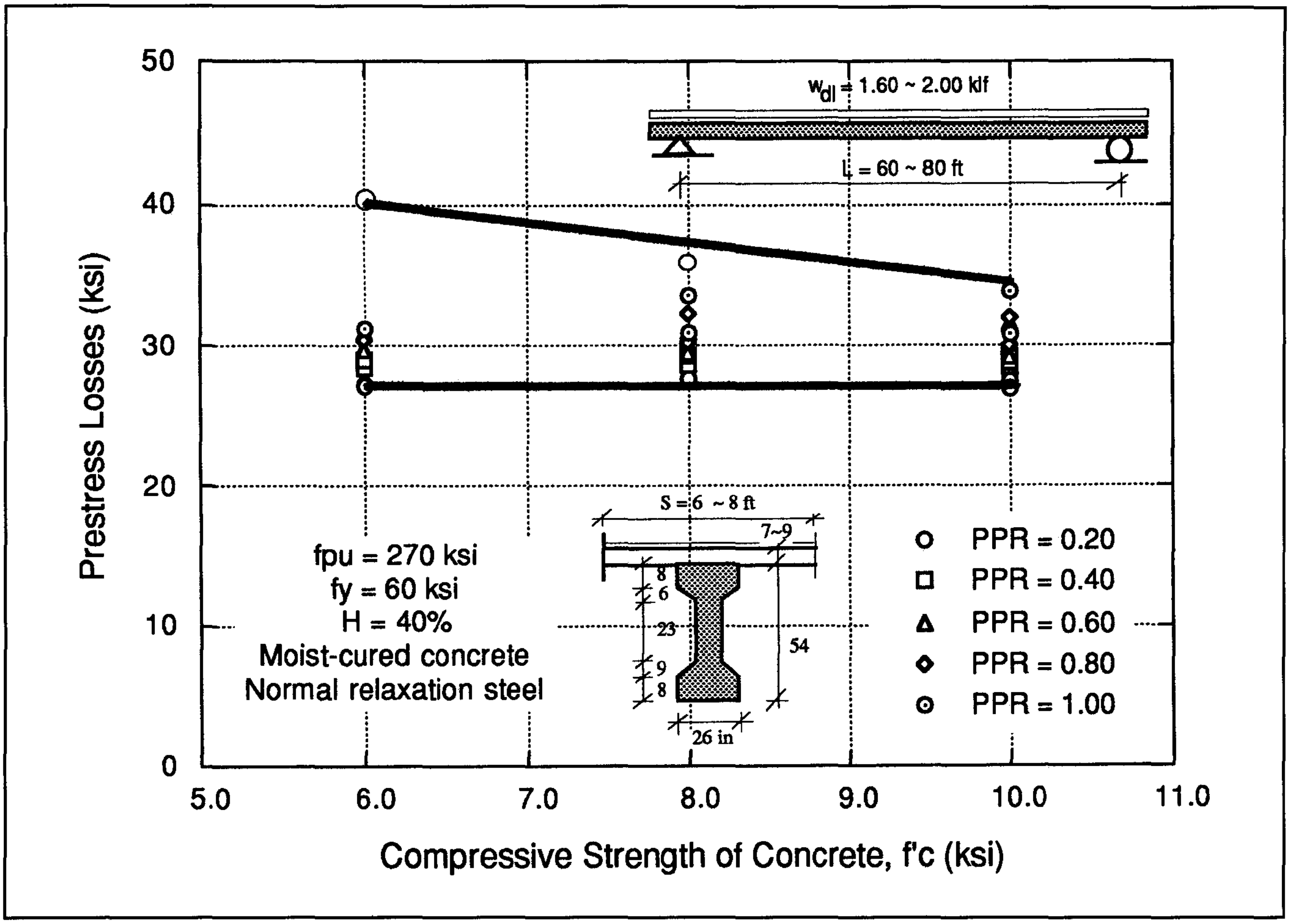

Fig. 4. Upper and lower limits of time-dependent losses for Study II.

sion that follow should be kept in perspective, particularly when the amount of non-prestressed reinforcement in the section is significant.

LIMITATIONS

The parametric evaluation undertaken in this study and the resulting recommendations for design (see Table 10) represent a first step toward improving the estimate of prestress losses in partially prestressed high strength concrete members. However, it is important to keep in mind that a number of limitations apply and to use engineering judgment whenever a particular situation occurs.

The following are some of the limitations of the study:

1. The dead load (sustained load) used to compute time-dependent losses was assumed to be fully applied at the end of the curing period; thus, the effect of different loading steps was not considered in the study.

2. Uncracked section analysis was conducted assuming that, even in the case of partially prestressed members, the dead load (sustained load) does not lead to cracking.

3. The prestressed and non-prestressed tensile reinforcement were assumed lumped at the same depth.

4. The effect of slab composite action was not considered.

5. Compressive reinforcement, if significant, was not considered.

Moreover, most computations in Studies II to V were carried out assuming a relative humidity of 40 percent. This leads to time-dependent losses 2 to 3 ksi (14 to 21 MPa) larger than at a relative humidity of 75 percent, which may be considered the average norm. However, the difference is somewhat integrated in the upper bound and average equations recommended in Table 10.

It should be pointed out that differences in TDL (see Table 10) between different types of sections may also be due to differences in the average level of prestress in the concrete; however, this parameter was not directly analyzed in this investigation.

Other parameters were not investigated, namely, the case of unbonded tendons whether internal or external. Because the stress in these tendons is assumed to be the same throughout the span, losses are expected to be, on the average, smaller than those suggested in Table 10.

DISCUSSION

Although this study leads to a lump sum estimate of prestress losses useful for design, it does not necessarily address the philosophy of how this information can be used. Ghali[24] has taken the position that the design process should follow a time-step analysis for all stresses in the materials and thus the stress in the prestressing steel at service life becomes only one variable to consider. The reason behind this approach is the concern that, in the presence of non-

Table 7. Prestress losses for simply supported partially prestressed pretensioned bridge box girders for Study III.

		f'_c = 6 ksi									f'_c = 8 ksi									f'_c = 10 ksi								
		f_{pu} = 145 ksi			f_{pu} = 235 ksi			f_{pu} = 270 ksi			f_{pu} = 145 ksi			f_{pu} = 235 ksi			f_{pu} = 270 ksi			f_{pu} = 145 ksi			f_{pu} = 235 ksi			f_{pu} = 270 ksi		
Span L (ft)	**PPR**	**TIL (ksi)**	**TDL (ksi)**	**TPL (ksi)**	**TIL (ksi)**	**TDL (ksi)**	**TPL (ksi)**	**TIL (ksi)**	**TDL (ksi)**	**TPL (ksi)**	**TIL (ksi)**	**TDL (ksi)**	**TPL (ksi)**	**TIL (ksi)**	**TDL (ksi)**	**TPL (ksi)**	**TIL (ksi)**	**TDL (ksi)**	**TPL (ksi)**	**TIL (ksi)**	**TDL (ksi)**	**TPL (ksi)**	**TIL (ksi)**	**TDL (ksi)**	**TPL (ksi)**	**TIL (ksi)**	**TDL (ksi)**	**TPL (ksi)**
50	0.20	0.1	13.9	14.0	0.1	20.3	20.3	0.1	22.7	22.7	0.1	13.9	14.0	0.2	20.3	20.5	0.1	22.7	22.8	0.0	14.0	14.0	0.0	20.4	20.4	0.0	22.8	22.8
	0.40	1.4	14.0	15.4	1.4	20.4	21.8	1.4	22.8	24.2	1.2	14.0	15.1	1.4	20.4	21.7	1.2	22.6	23.8	1.0	13.9	15.0	1.0	20.3	21.4	1.0	22.7	23.8
	0.60	2.7	14.1	16.8	2.7	20.5	23.3	2.7	22.9	25.7	2.3	14.0	16.3	2.5	20.4	22.9	2.4	22.4	24.8	2.1	13.9	16.0	2.1	20.3	22.4	2.1	22.7	24.8
	0.80	4.1	14.3	18.3	4.2	20.7	24.8	4.2	23.1	27.2	3.5	14.0	17.6	3.7	20.4	24.1	3.6	22.2	25.8	3.2	13.9	17.0	3.2	20.2	23.4	3.2	22.6	25.8
	1.00	5.5	14.4	19.9	5.7	20.8	26.5	5.7	23.2	28.9	4.8	14.1	18.9	4.9	20.5	25.4	4.9	22.1	27.0	4.3	13.8	18.1	4.4	20.2	24.6	4.4	22.6	27.0
60	0.20	0.4	13.5	13.9	0.4	19.9	20.3	0.4	22.3	22.7	0.3	13.6	14.0	0.3	20.0	20.3	0.3	22.5	22.8	0.3	13.7	14.0	0.3	20.1	20.4	0.3	22.5	22.8
	0.40	2.5	13.7	16.2	2.5	20.1	22.6	2.5	22.5	25.0	2.1	13.7	15.8	2.1	20.1	22.2	2.0	22.4	24.3	1.9	13.7	15.6	1.9	20.1	21.9	1.9	22.5	24.3
	0.60	4.6	13.9	18.5	4.7	20.3	25.0	4.7	22.7	27.4	3.9	13.8	17.7	4.0	20.1	24.2	3.8	22.2	26.0	3.5	13.6	17.2	3.6	20.0	23.6	3.6	22.4	26.0
	0.80	6.8	14.2	21.0	7.0	20.5	27.5	7.0	22.9	30.0	5.8	13.9	19.7	6.0	20.2	26.2	5.6	22.1	27.7	5.2	13.6	18.8	5.4	19.9	25.3	5.4	22.3	27.7
	1.00	9.0	14.5	23.5	9.4	20.8	30.2	9.5	23.5	33.0	7.8	14.0	21.7	8.1	20.3	28.4	7.6	21.9	29.5	7.0	13.6	20.5	7.2	19.9	27.1	7.2	22.3	29.5
70	0.20										0.8	13.2	14.0	0.8	19.6	20.4	0.8	22.0	22.8	0.7	13.4	14.1	0.7	19.7	20.4	0.7	22.1	22.8
	0.40										3.5	13.2	16.7	3.5	19.6	23.2	3.5	21.6	25.2	3.1	13.3	16.4	3.1	19.7	22.8	3.1	22.0	25.2
	0.60										6.2	13.4	19.6	6.2	19.9	26.1	6.4	21.2	27.6	5.5	13.2	18.7	5.7	19.6	25.2	5.7	22.0	27.6
	0.80										8.9	13.5	22.5	9.3	19.8	29.2	9.4	20.8	30.2	8.0	13.2	21.2	8.3	19.5	27.8	8.3	21.9	30.2
	1.00										11.7	13.7	25.5	12.4	20.0	32.4	12.6	20.4	33.0	10.5	13.2	23.7	11.1	19.4	30.5	11.2	21.8	33.0

Notes:

1. Design data: Type IV-36 AASHTO bridge girder; four traffic lanes bridge; and HS-20 truck loading.
2. Reference base: Moist-cured concrete; normal steel relaxation; f_y = 60 ksi; and H = 40 percent.
3. TDL = Time-Dependent Losses = Creep of Concrete + Shrinkage of Concrete + Relaxation of Steel.
4. TIL = Time-Independent Losses = Elastic Shortening.
5. Total Prestress Losses, TPL = TDL + TIL.

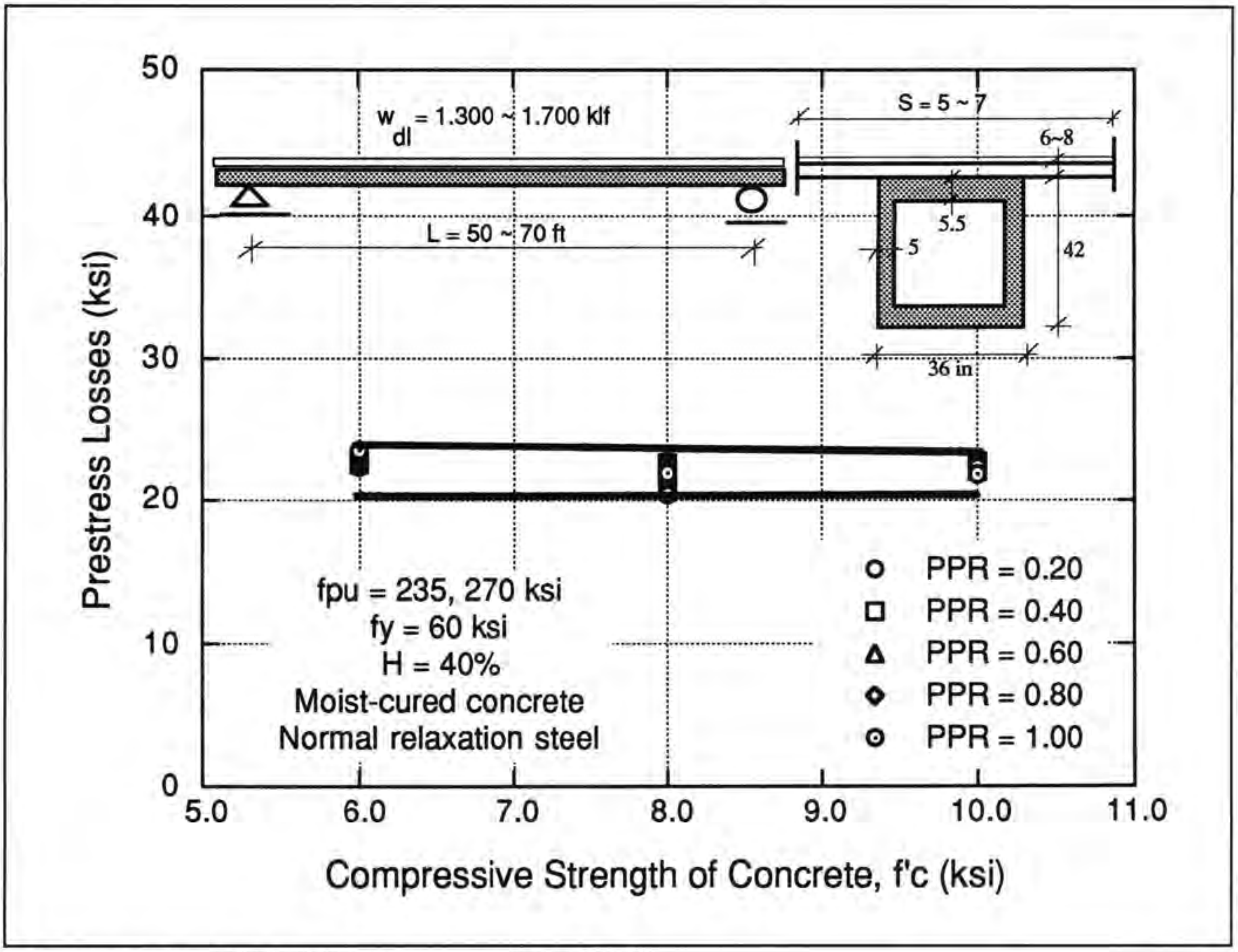

Fig. 5. Upper and lower limits of time-dependent losses for Study III.

prestressed tension and/or compression reinforcement, the tensile force loss in the prestressing steel is not equal to the loss of compression in the concrete.

The difference between the two quantities, which represents a change in force in the non-prestressed steel, ΔT_s, may be sufficiently large to cause false predictions of the structural behavior under service load. In particular, a predicted long-term deflection may in fact lead to a camber, or vice-versa, or a predicted uncracked section may lead to a cracked one. This also has been pointed out in several prior

Table 8. Prestress losses for simply supported pretensioned prestressed hollow-core slabs for Study IV.

Type of section	Span L (ft)	$f'_c = 6$ ksi							$f'_c = 8$ ksi							$f'_c = 10$ ksi						
		Individual losses				TDL	TIL	TPL	Individual losses				TDL	TIL	TPL	Individual losses				TDL	TIL	TPL
		CC	SC	RE	ES	(ksi)	(ksi)	(ksi)	CC	SC	RE	ES	(ksi)	(ksi)	(ksi)	CC	SC	RE	ES	(ksi)	(ksi)	(ksi)
4HC8	20	5.8	16.3	14.2	4.2	36.4	4.2	40.6	4.2	16.3	14.6	3.6	35.1	3.6	38.7	2.9	16.3	14.9	3.2	34.2	3.2	37.4
	25	9.5	16.3	12.9	6.9	38.8	6.9	45.7	6.7	16.3	13.6	5.8	36.6	5.8	42.4	4.8	16.3	14.1	5.1	35.2	5.1	40.3
	30	14.5	16.3	11.2	10.6	42.1	10.6	52.7	10.1	16.3	12.3	8.7	38.7	8.7	47.5	7.1	16.3	13.0	7.6	36.5	7.6	44.1
4HC10	25	6.5	15.9	14.0	4.8	36.3	4.8	41.2	4.6	15.9	14.5	4.1	34.9	4.1	39.0	3.3	15.9	14.8	3.6	34.0	3.6	37.6
	30	9.6	15.9	12.9	7.2	38.4	7.2	45.6	6.8	15.9	13.6	6.1	36.2	6.1	42.3	4.8	15.6	14.1	5.4	34.8	5.4	40.1
	35	13.6	15.9	11.5	10.3	41.0	10.3	51.3	9.5	15.6	12.5	8.6	37.9	8.6	46.5	6.7	15.6	13.2	7.5	35.8	7.5	43.3
4HC12	30	8.9	15.9	13.2	6.5	38.0	6.5	44.5	6.4	15.9	13.8	5.6	36.1	5.6	41.6	4.5	15.9	14.2	4.9	34.7	4.9	39.6
	35	12.3	15.9	12.0	9.1	40.2	9.1	49.4	8.8	15.9	12.9	7.7	37.5	7.7	45.2	6.3	15.9	13.5	6.8	35.6	6.8	42.5
	40	16.4	15.9	10.6	12.3	43.0	12.3	55.2	11.6	15.9	11.8	10.3	39.3	10.3	49.6	8.3	15.9	12.5	9.1	36.8	9.1	45.8

Notes:

1. Design data: PCI standard sections; building structure; and ACI Building Code (ACI 318-89).
2. Reference base: Moist-cured concrete; normal relaxation steel; $f_{pu} = 235$ ksi; and $H = 40$ percent.
3. TDL = Time-Dependent Losses = Creep of Concrete + Shrinkage of Concrete + Relaxation of Steel.
4. TIL = Time-Independent Losses = Elastic Shortening.
5. Total Prestress Losses, TPL = TDL + TIL.

Table 9. Prestress losses for simply supported prestressed pretensioned double tee beams for Study V.

Type of section	Span L (ft)	$f'_c = 6$ ksi							$f'_c = 8$ ksi							$f'_c = 10$ ksi						
		Individual losses				TDL	TIL	TPL	Individual losses				TDL	TIL	TPL	Individual losses				TDL	TIL	TPL
		CC	SC	RE	ES	(ksi)	(ksi)	(ksi)	CC	SC	RE	ES	(ksi)	(ksi)	(ksi)	CC	SC	RE	ES	(ksi)	(ksi)	(ksi)
8DT16	20	6.9	16.1	13.9	5.0	36.8	5.0	41.8	5.0	16.1	14.3	4.3	35.4	4.3	39.7	3.6	16.1	14.7	3.9	34.3	3.9	38.2
	30	14.4	16.1	11.2	10.9	41.7	10.9	52.5	10.5	16.1	12.1	9.4	38.7	9.4	48.1	7.7	16.1	12.8	8.4	36.5	8.4	44.9
	40	23.2	16.1	8.2	18.5	47.5	18.5	65.9	17.3	16.1	9.5	16.0	42.9	16.0	58.9	12.8	16.1	10.5	14.4	39.3	14.4	53.7
8DT20	30	9.9	16.0	12.7	7.5	38.7	7.5	46.1	7.3	16.0	13.4	6.5	36.7	6.5	43.1	5.3	16.0	13.9	5.8	35.1	5.8	40.9
	40	16.3	16.0	10.5	12.6	42.8	12.6	55.4	12.1	16.0	11.5	11.0	39.6	11.0	50.5	8.8	16.0	12.2	9.8	37.1	9.8	46.9
	50	23.3	16.0	8.2	18.8	47.4	18.8	66.2	17.5	16.0	9.4	16.4	42.9	16.4	59.2	12.9	16.0	10.4	14.7	39.3	14.7	54.0
8DT24	40	12.2	15.7	12.0	9.3	39.8	9.3	49.1	9.0	15.7	12.7	8.1	37.4	8.1	45.5	6.5	15.7	13.3	7.3	35.5	7.3	42.8
	50	17.5	15.7	10.1	13.8	43.3	13.8	57.1	13.1	15.7	11.1	12.0	39.9	12.0	51.9	9.6	15.7	11.9	10.8	37.2	10.8	48.0
	60	23.0	15.7	8.2	18.9	46.9	18.9	65.8	17.4	15.7	9.4	16.5	42.5	16.5	59.0	12.9	15.7	10.4	14.8	39.0	14.8	53.8

Notes:

1. Design data: PCI standard sections; building structure; and ACI Building Code (ACI 318-89).
2. Reference base: Moist-cured concrete; normal relaxation steel; $f_{pu} = 235$ ksi; and $H = 40$ percent.
3. TDL = Time-Dependent Losses = Creep of Concrete + Shrinkage of Concrete + Relaxation of Steel.
4. TIL = Time-Independent Losses = Elastic Shortening.
5. Total Prestress Losses, TPL = TDL + TIL.

studies by Tadros, Ghali, et al.[6,12,17,24]

In attempting to provide a simple answer to this problem, Tadros, et al.,[12] suggested that the loss of compression in the concrete can be computed as a first approximation from the following expression:

$$\Delta C_c = \Delta F_p + \Delta T_s \qquad (18)$$

where ΔF_p is the loss of tensile force in the prestressing steel due to prestress losses and ΔT_s can be estimated from:

$$\Delta T_s = (\Delta f_{pS} + \Delta f_{pC})\, A_s \qquad (19)$$

in which Δf_{pS} and Δf_{pC} can be computed from Eqs. (5) and (8), respectively, and A_s is the area of non-prestressed steel

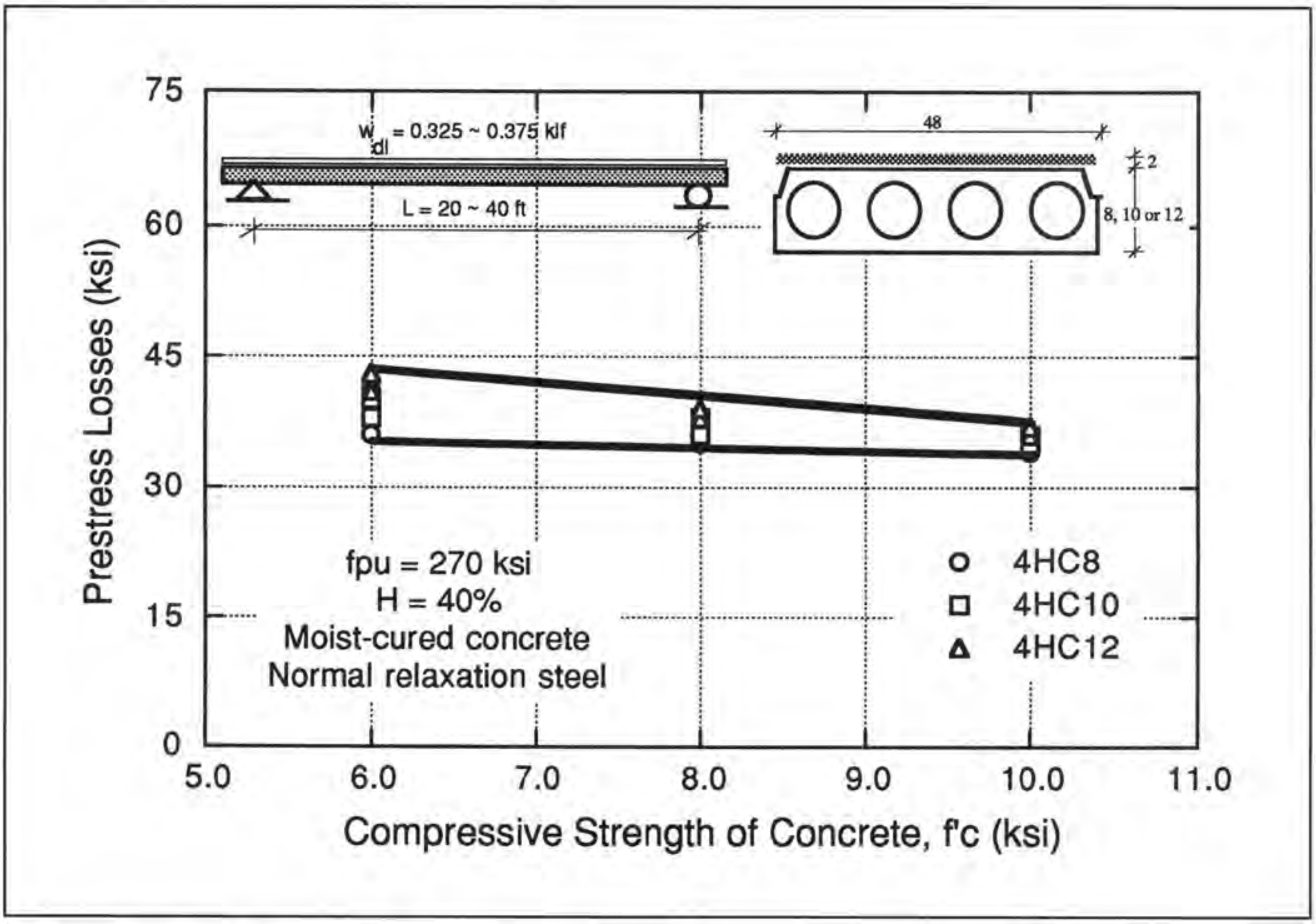

Fig. 6. Upper and lower limits of time-dependent losses for Study IV.

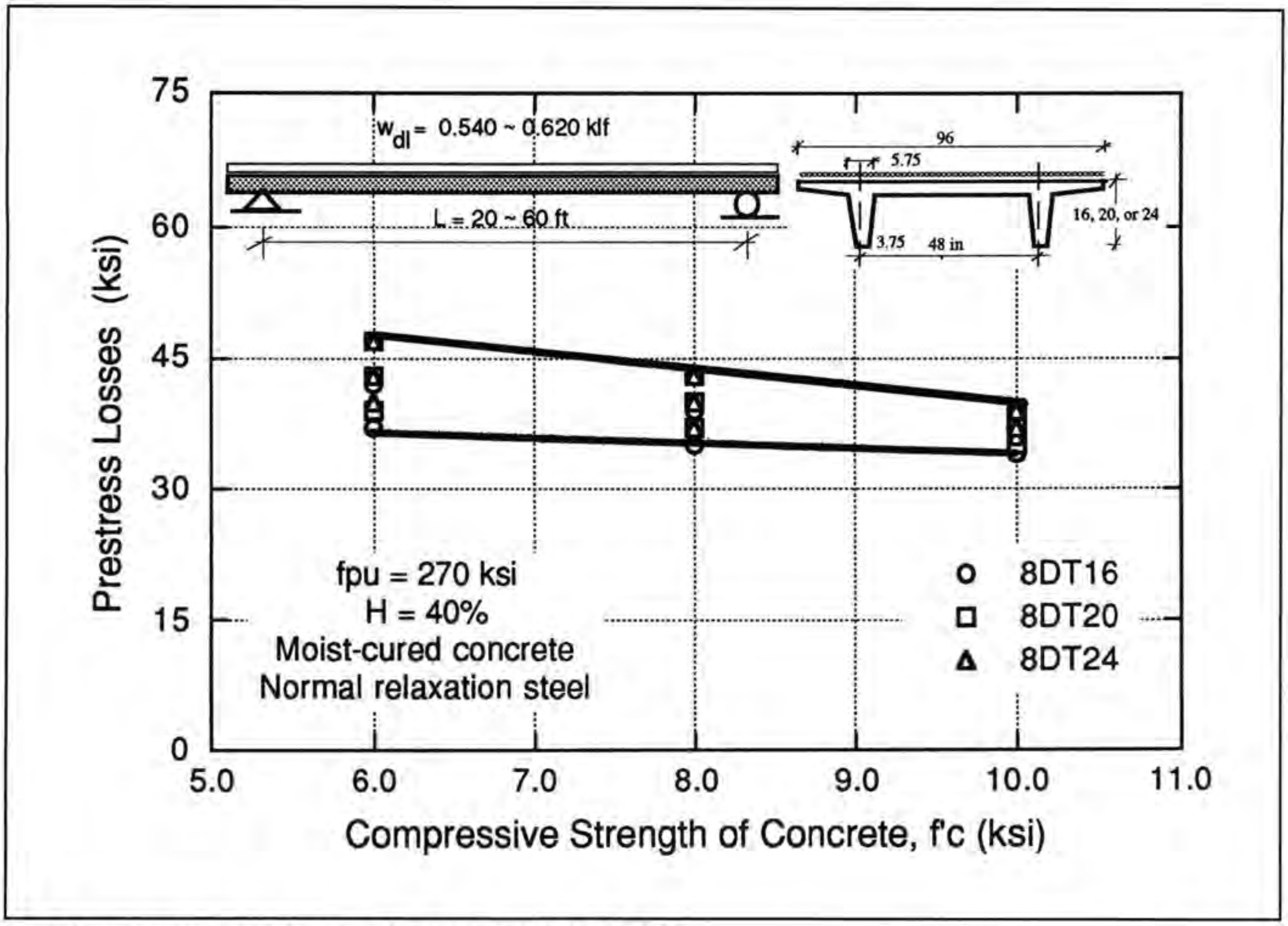

Fig. 7. Upper and lower limits of time-dependent losses for Study V.

Table 10. Recommended lump sum estimates of time-dependent losses (creep, shrinkage, relaxation).

Type of beam or section	Bound	Time-dependent losses for wires and strands with f_{pu} = 235, 250 or 270 ksi (1620, 1725 or 1860 MPa)†	Time-dependent losses for bars with f_{pu} = 145 and 160 ksi (1000 and 1100 MPa)*
Rectangular, solid slab, I-girder	Upper bound	29 + 4 PPR (ksi) 203 + 28 PPR (MPa)	19 + 6 PPR (ksi) 133 + 42 PPR (MPa)
	Average	26 + 4 PPR (ksi) 182 + 28 PPR (MPa)	
Box girder	Upper bound	21 + 4 PPR (ksi) 174 + 28 PPR (MPa)	15 (ksi) 105 (MPa)
	Average	19 + 4 PPR (ksi) 133 + 28 PPR (MPa)	
Single tee, double tee, hollow-core slab	Upper bound	$39\left[1-0.15\frac{f_c'-6}{6}\right]+6$ PPR (ksi) $273\left[1-0.15\frac{f_c'-42}{42}\right]+42$ PPR (MPa)	$31\left[1-0.15\frac{f_c'-6}{6}\right]+6$ PPR (ksi) $217\left[1-0.15\frac{f_c'-42}{42}\right]+42$ PPR (MPa)
	Average	$33\left[1-0.15\frac{f_c'-6}{6}\right]+6$ PPR (ksi) $231\left[1-0.15\frac{f_c'-42}{42}\right]+42$ PPR (MPa)	

Notes:

* The upper bound and the average values are the same for prestressing bars.

† For low-relaxation strands, reduce the values recommended by 4 ksi (28 MPa) for box girders, 6 ksi (41 MPa) for rectangular beams, solid slabs and I-girders, and 8 ksi (55 MPa) for single tees, double tees and hollow-core slabs.

‡ For structural lightweight concrete, increase the values recommended by 5 ksi (34 MPa).

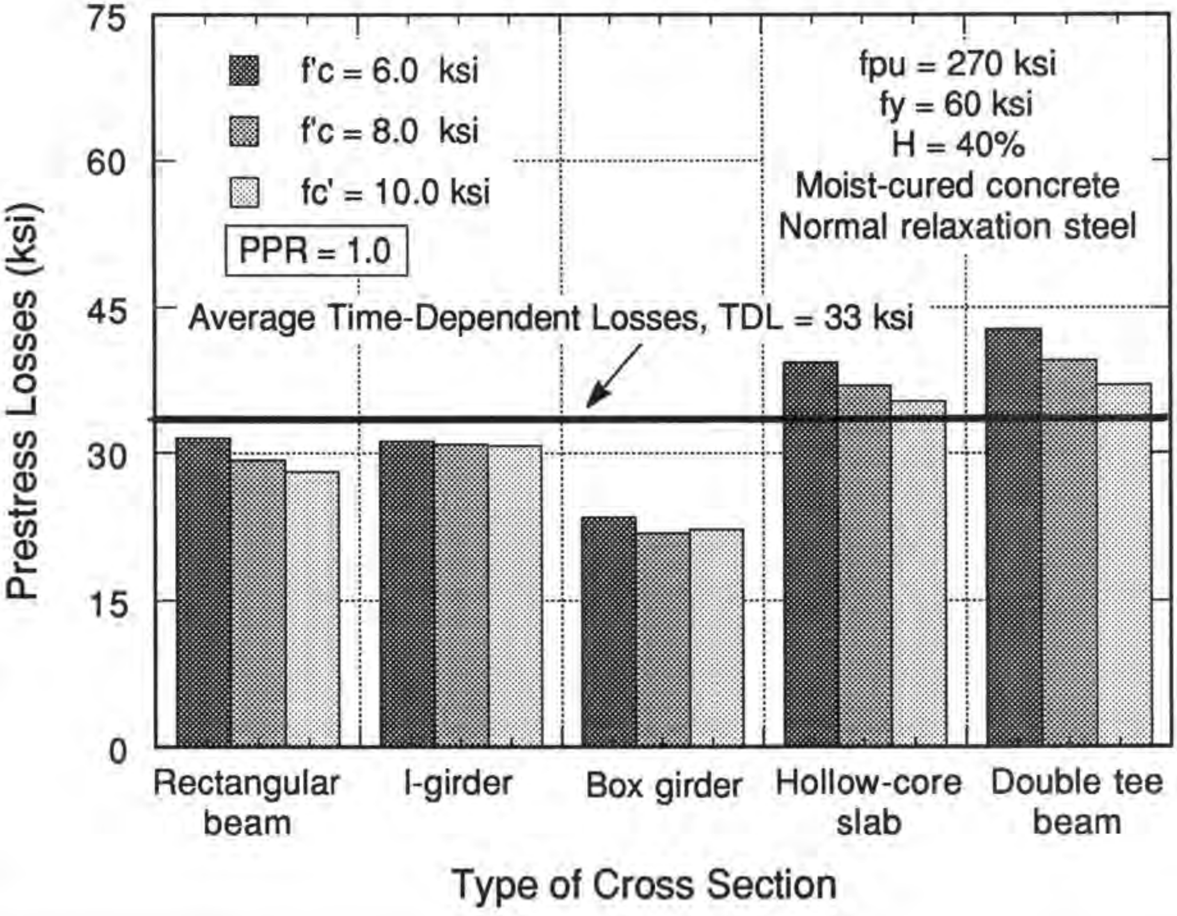

Fig. 8. Effect of type of cross section on time-dependent losses in fully prestressed beams.

assumed centered at the same depth as the prestressing steel. The forces C_c, F_p and T_s must satisfy force and moment equilibrium of the section and the value of C_c should be used in computing stresses in the concrete at any time t.

CONCLUSIONS

This study confirmed either a number of observations made in previous studies, or a number of logical inferences on the effects of shrinkage, creep and relaxation on time-dependent prestress losses in partially prestressed concrete members. Additional relevant conclusions can be drawn as follows:

1. The prestress loss due to creep decreases with a decrease in the partial prestressing ratio, PPR; however, the loss due to relaxation of the prestressing steel increases with a decrease in PPR. Because creep and relaxation losses influence each other, there is a somewhat balancing effect between them. This balancing effect is less apparent for low-relaxation steel.

2. Everything else being equal, the time-dependent stress loss in the prestressing steel, TDL, generally decreases with a decrease in the partial prestressing ratio, PPR. Up to a 30 percent decrease was observed when PPR decreased from 1 to 0.2.

3. Everything else being equal, the time-dependent stress loss in the prestressing steel, TDL, generally decreases with an increase in the concrete compressive strength. Up to a 20 percent decrease was observed when f_c' varied from 6 to 10 ksi (41 to 69 MPa).

4. Time-dependent losses are influenced by the type of cross section (see Fig. 8). Highest losses were observed for fully prestressed double-tee beams and hollow-core slabs used primarily for building structures. Average losses were observed for the AASHTO type I-girders and rectangular beams; relatively smaller losses were observed for box girders. Lump sum estimates of time-dependent losses (as influenced by the type of section) are recommended for design and are summarized in Table 10.

5. As expected, the loss due to elastic shortening decreases with a decrease in the level of prestress, i.e., with a decrease in the partial prestressing ratio, PPR. For the parameters used in this study, elastic shortening loss varied from 0 to 19 ksi (131 MPa). This loss represents up to 10 percent of the initial prestress in the steel. Thus, it is strongly recommended, in any lump sum estimate of losses, to separate the effect of elastic shortening, which is instantaneous and can be easily calculated, from time-dependent losses, TDL.

6. The results of this study (and particularly Conclusion

5) suggest that the current estimates of lump sum values of prestress losses recommended in the AASHTO Specifications[14] (see Table, Section 1.6.7) and in the report of ACI-ASCE Committee 343[15] (see Table 9.6.4.1) should not be used due to several reasons, namely: (1) they lump together elastic shortening (an instantaneous loss) with time-dependent losses, (2) they are insensitive to the partial prestressing ratio and the type of concrete section, and (3) they do not cover the influence of the concrete compressive strength beyond 6 ksi (41 MPa). In waiting for additional investigations and for an improvement in the state-of-the-art regarding prestress losses, the lump sum estimates of time-dependent losses shown in Table 10 are recommended for design.

7. It should be kept in mind that, in partially prestressed concrete members, the loss of compression force in the concrete due to time-dependent effects is not equal to the loss of tension force in the prestressing steel. The difference between them, which is equal to the change in force in the non-prestressed steel, can be very significant and should be accounted for in a service load analysis.[12,17,24]

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REFERENCES

1. ACI-ASCE Committee 423, "Tentative Recommendations for Prestressed Concrete," *ACI Journal,* V. 54, No. 7, January 1958, pp. 545-578.
2. Branson, D. E., and Kripanarayanan, A., "Loss of Prestress, Camber, and Deflection of Non-Composite and Composite Prestressed Concrete Structures," PCI JOURNAL, V. 16, No. 5, September- October 1971, pp. 22-52.
3. Glodowski, R. J., and Lorenzetti, J. J., "A Method for Predicting Prestress Losses in a Prestressed Concrete Structure," PCI JOURNAL, V. 17, No. 2, March-April 1972, pp. 17-31.
4. Grouni, H. N., "Prestressed Concrete: A Simplified Method for Loss Computation," *ACI Journal,* Proceedings, V. 70, No. 2, February 1973, pp. 15-29.
5. Hernandez, H. D., and Gamble, W. L., "Time-Dependent Losses in Pretensioned Concrete Construction," Structural Research Series No. 417, Civil Engineering Studies, University of Illinois, Urbana, IL, May 1975, 171 pp.
6. Tadros, M. K., Ghali, A., and Dilger, W. H., "Time-Dependent Prestress Loss and Deflection in Prestressed Concrete Members," PCI JOURNAL, V. 20, No. 3, May-June 1975, pp. 86-98.
7. PCI Committee on Prestress Losses, "Recommendations for Estimating Prestress Losses," PCI JOURNAL, V. 20, No. 4, July-August 1975, pp. 43-75.
8. Tadros, M. K., Ghali, A., and Dilger, W. H., "Effect of Non-Prestressed Steel on Prestress Loss and Deflection," PCI JOURNAL, V. 22, No. 2, March-April 1977, pp. 50-63.
9. Zia, P., Preston, H. K., Scott, N. L., and Workman, E. B., "Estimating Prestress Losses," *Concrete International,* V. 1, No. 6, June 1979, pp. 32-38.
10. Huang, T., "Study of Prestressed Losses Conducted by Lehigh University," PCI JOURNAL, V. 27, No. 5, September-October 1982, pp. 48-61.
11. FIP Recommendations, "Practical Design of Reinforced and Prestressed Concrete Structures," based on CEB-FIP Model Code MC 78, Thomas Telford Limited, London, 1984.
12. Tadros, M. K., Ghali, A., and Meyer, A. W., "Prestress Loss and Deflection of Precast Concrete Members," PCI JOURNAL, V. 30, No. 1, January-February 1985, pp. 114-141.
13. *Prestressed Concrete,* Pennsylvania Department of Transportation, V. 1 and V. 3, Part B, Section 9, 1985.
14. AASHTO, *Standard Specifications for Highway Bridges,* Fifteenth Edition, American Association of State Highway and Transportation Officials, Washington, D.C., 1992.
15. ACI-ASCE Committee 343, "Analysis and Design of Reinforced Concrete Bridge Structures," Report No. 343R-88, American Concrete Institute, Detroit, MI, 1988, pp. 106-116.
16. Naaman, A. E., *Prestressed Concrete Analysis and Design: Fundamentals,* McGraw-Hill Book Company, New York, NY, 1982, 694 pp.
17. Ghali, A., and Favre, R., *Concrete Structures: Stresses and Deformations,* Chapman and Hall, London-New York, 1986, 352 pp.
18. ACI Committee 209, "Prediction of Creep, Shrinkage and Temperature Effects in Structures," Special Publication SP-27, *Designing for Creep, Shrinkage and Temperature,* American Concrete Institute, Detroit, MI, 1971, pp. 51-93.
19. Bažant, Z. P., and Kim, J-K., "Improved Prediction Model for Time-Dependent Deformations of Concrete: Part 2 — Basic Creep," *Materials and Structures/Materiaux et Construction,* V. 24, No. 144, RILEM, Paris, November 1991, pp. 409-421.
20. Naaman, A. E., and Siriaksorn, A., "Serviceability Based Design of Partially Prestressed Beams," PCI JOURNAL, V. 24, No. 3, May-June 1979, pp. 64-89.
21. ACI Committee 318, "Building Code Requirements for Reinforced Concrete (ACI 318-89)" and "Commentary on Building Code Requirements for Reinforced Concrete (ACI 318R-89)," American Concrete Institute, Detroit, MI, 1989.
22. Naaman, A. E., and Hamza, A. M., "Evaluation of Prestress Losses for Partially Prestressed High Strength Concrete Beams," Report No. UMCE 91-18, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, August 1991.
23. *PCI Design Handbook — Precast and Prestressed Concrete,* Fourth Edition, Precast/Prestressed Concrete Institute, Chicago, IL, 1992.
24. Ghali, A., "Stress and Strain Analysis in Prestressed Concrete: A Critical Review," PCI JOURNAL, V. 34, No. 6, November-December 1989, pp. 80-97.

APPENDIX A — LUMP SUM ESTIMATES OF PRESTRESS LOSSES

Table A1, taken from ACI 343R-88 (Table 9.6.4.1), provides lump sum estimates of prestress losses (including elastic shortening and time-dependent losses) for both pretensioned and post-tensioned concrete members.

Table A1. Elastic and time-dependent losses.*

Type of prestressing	f'_c = 4000 psi (28 MPa)	f'_c = 5000 psi (34 MPa)	f'_c = 6000 psi (41 MPa)
Pretensioning with strand		45,000 psi (310 MPa)	45,000 psi (310 MPa)
Post-tensioning with strand or wire	32,000 psi (221 MPa)	33,000 psi (228 MPa)	35,000 psi (241 MPa)
Post-tensioning with high tensile bars	22,000 psi (152 MPa)	23,000 psi (159 MPa)	24,000 psi (165 MPa)

* Applies to bridges exposed to average conditions with prestress levels inducing maximum stresses close to those specified in Section 8.7, ACI 343R-88.

APPENDIX B — NOTATION

A_c = transformed area of concrete at section considered

A_{ps} = area of prestressing steel in tension zone

A_s = area of non-prestressed tensile steel

b = parameter; equals 35 for moist-cured concrete and 55 for steam-cured concrete

C_{CU} = ultimate creep coefficient of concrete material

E_c = modulus of elasticity of concrete at 28 days

E_{ci} = modulus of elasticity of concrete at release

E_{ps} = modulus of elasticity of prestressing steel

e_o = prestressing force eccentricity at section considered

F_J = prestressing force at end of jacking

$(f_{cgs})_{F_J}$ = stress in concrete at centroid of prestressing steel due to the force F_J

$(f_{cgs})_G$ = stress in concrete at centroid of prestressing steel due to self weight of member

$f_{cgs}(t_i)$ = stress in concrete at centroid of prestressing steel at time t_i due to prestressing force and dead load

f_{pJ} = stress in prestressing steel at end of jacking

$f_{ps}(t_i)$ = stress in prestressing steel at time t_i, at section considered

f_{py} = yield strength of prestressing steel

$g(t_i), g(t_j)$ = time functions at time t_i and t_j

H = relative humidity in percent

I = transformed moment of inertia of section considered

K_{CA} = age at loading factor for creep

K_{CH} = correction factor of humidity for creep for both moist- and steam-cured concrete

K_{CS} = shape and size factor for creep

K_{SH} = correction factor for shrinkage due to relative humidity

K_{SS} = shape and size factor for shrinkage

M_D = moment due to dead load

M_G = moment due to self weight of member

n_p = modular ratio = E_{ps}/E_c

n_{pi} = initial modular ratio = E_{ps}/E_{ci}

r = radius of gyration of cross section

t_A = age at loading in days

t_i, t_j = respectively, the beginning and end of a time interval

$\frac{V}{S}$ = volume to surface ratio of member

ΔC_c = loss of compression in concrete

ΔF_p = loss of tensile force in prestressing steel due to prestress losses

Δf_{pES} = loss in prestressing steel stress due to elastic shortening

$\Delta f_{pR}(t_0, t_t)$ = relaxation loss of prestressing steel stress during the time interval (t_0, t_t), i.e., time of stressing to time of transfer

$\Delta f_{pR}(t_i, t_j)$ = loss in prestressing steel stress due to relaxation of steel over time interval (t_i, t_j)

$\Delta f_{pS}(t_i, t_j)$ = loss in prestressing steel stress due to shrinkage of concrete over time interval (t_i, t_j)

$\Delta f_{pC}(t_i, t_j)$ = loss in prestressing steel stress due to creep of concrete over time interval (t_i, t_j)

ΔT_s = loss of tensile force in non-prestressed steel

ε_{SU} = ultimate shrinkage strain of concrete material