Guide to Estimating Prestress Loss

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This guide is intended for estimation of prestress losses in concrete structures. Methods presented include lump sum, simplified approaches addressing individual source of loss, and additional estimation methods. They address losses in pretensioned and post-tensioned members, including bonded, unbonded, and external tendons. Note that these estimation methods have not been evaluated for relative merits. A discussion of the variability of prestress losses caused by the variability in concrete properties is also presented. Several example problems are included.

Keywords: creep; friction; post-tensioning; prestress loss; prestressed concrete; relaxation; shrinkage.

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CHAPTER 1—INTRODUCTION

1.1—Introduction

Estimating prestress loss at any given time during the life of a prestressed concrete member is a complex issue. In pretensioned and post-tensioned members, applying prestressing force causes shortening of the concrete member that, in turn, causes a loss of tendon stress. Over time, concrete creep, concrete shrinkage, and steel relaxation result in additional reductions of tendon stress. In post-tensioned members, losses occur during the stressing operation due to friction between the tendon and sheathing or duct, which is caused by the intended and unintended tendon curvature. There are also losses due to seating of the wedges or nuts as the jacking force is transferred into the anchorage device. These and other sources of prestress loss are examined by the licensed design professional to get an estimate of the total prestress loss and resulting effective prestressing force.

Losses have inherent variability due to variations of material properties and environmental and curing conditions. Some losses may affect others. Time-dependent concrete properties are particularly difficult to estimate accurately, so losses due to creep and shrinkage are expected to be variable. Friction between the tendon and sheathing or duct, movement of wedges within the anchorage device, and modulus of elasticity of concrete are also variables. The variability within each component and the interdependence among the components make it understandable that studies comparing measured prestress losses to predictions have shown that accurate and consistent calculation of prestress loss is difficult to achieve.

The best effort to calculate prestress loss is only an estimate and, therefore, the licensed design professional should consider the consequences of actual losses being higher or lower than the estimated value. Estimation of prestress loss is an important factor for evaluating the serviceability of all types of prestressed members and the calculation of flexural strength of members with unbonded tendons. The estimation of prestress loss, however, is not a significant factor in determination of flexural strength of bonded prestressed members. When computing the shear strength of prestressed members with little or no transverse reinforcement, a conservative estimate of the effective prestressing force is warranted.

1.2—Scope

ACI 318-11 requires that the design of prestressed concrete members allow for prestress loss; however, the required level of detail for calculating losses is unspecified. The friction loss provisions for post-tensioned construction that first appeared in ACI 318-63 were removed from ACI 318-11. Although ACI 318-11 Commentary indicates that the lump sum method is obsolete, the licensed design professional's requirement to choose a method to compute losses remains. This guide is intended to aid the designer in this choice by providing an overview of the various methods available.

Many participants in the design and construction process need information on prestress losses. The licensed design professional, precasters, and post-tensioners all need an understanding of, and method to estimate, aspects of losses. To which entity is responsible for calculation of each type of loss has to be clearly defined in the contract documents.

Total losses, Δf_{pT}, are losses due to friction and seating Δf_{pFS}, elastic shortening Δf_{pES}, creep of concrete Δf_{pCR}, shrinkage of concrete Δf_{pSH}, and relaxation of tendons Δf_{pRE}. This can be expressed as Eq. (1.2)

$$\Delta f_{pT} = \Delta f_{pFS} + \Delta f_{pES} + \Delta f_{pCR} + \Delta f_{pSH} + \Delta f_{pRE} \quad (1.2)$$

This guide presents background information and methods to calculate each type of loss.

Following the introduction and a list of notation and definitions, Chapter 3 includes a historical account of the lump sum method, currently recommended values for preliminary design, and a summary of losses that have been measured in field and laboratory studies.

Chapter 4 discusses the different types of initial losses and addresses the differences between pretensioned and post-tensioned members.

Chapter 5 presents a simplified approach to estimate long-term losses due to creep, shrinkage, and relaxation for pretensioned and post-tensioned concrete members.

Detailed approaches to estimate long-term losses are presented in Chapter 6, which also addresses changes in prestressing force caused by differential shrinkage and hydration of the concrete deck in composite members. The approaches can be used for pretensioned or post-tensioned members.

Chapter 7 discusses the variability of prestress loss calculations caused by concrete material properties, including compressive strength at transfer, modulus of elasticity, and creep and shrinkage.

Chapter 8 presents example problems and compares solutions from different methods.

1.3—Historical development

The concept of prestressing concrete dates back to the late 1800s (Naaman 2012). The performance of early prestressed concrete structures was adversely affected by time-dependent strains in the concrete—for example, creep and shrinkage, which were nearly as large as the initial steel strain due to prestressing. Before 1940, the initial steel strain induced by prestressing was limited by the low yield strength of steel. French engineer Eugene Freyssinet recognized the significance of prestress losses and the need for steels with high yield strength for prestressed applications. By 1945, higher strength steel became available, making it possible to produce the initial prestressing strain large enough so that the time-dependent strains developed in the concrete would not overcome the initial prestressing strain. As a result, the remaining prestressing force in the steel would be sufficiently large to be effective.

Prestress losses were first addressed by ACI 318 in 1963. Although the provisions catalogued the different causes of prestress loss, they only provided specific instruction on determining friction losses. These code provisions were based on an earlier committee publication that provided similar, slightly more detailed guidance on prestress loss (ACI-ASCE Committee 323 1958).

In the 1970s, the Precast/Prestressed Concrete Institute (PCI Committee on Prestress Losses 1975) and Zia et al. (1979) provided more detailed methods to estimate prestress losses. Since the 1970s, others have developed methods to estimate prestress losses (Tadros et al. 2003; Seguirant and Anderson 1985; Youakim et al. 2007; Garber et al. 2013). Gilbert and Ranzi (2011) and Branson (1977) provide general approaches to the calculation of a variety of time-dependent effects in concrete structures, including prestress losses. Computer programs have been developed to perform the tedious calculations required for stepwise analyses of prestress loss. However, due to the inherent uncertainties associated with material properties, construction practices, and in-service conditions, even the most refined calculations result in prestress loss predictions that differ from measured values.

1.3.1 *Currently available guidance on estimating prestress losses*—For pretensioned building products, the *PCI Design Handbook* (PCI 2010) presents a method to estimate prestress losses based on the method developed by Zia et al. (1979). This method is widely used for building structures and is referenced in the R18.6.1 commentary of ACI 318-11, and presented in this guide in Chapter 5. For bridge beams, the "AASHTO LRFD Bridge Design Specification" (AASHTO 2012) presents two methods. One is an approximate method and the other a refined method based on several parameters to estimate prestress losses. The refined method could be applied to building products as well. These methods are presented in Chapters 5 and 6.

1.4—Guide organization and use

This guide presents a variety of approaches for estimating prestress losses in pretensioned and post-tensioned members. This section identifies relevant sections of interest in the guide, depending on member type (pretensioned or post-tensioned) and level of effort (lump sum, simplified, or detailed). The lump sum method is only recommended for preliminary designs. The simplified method is appropriate for most typical designs. Detailed methods are most often used for more complex structures, which may have staged construction and prestressing operations.

1.4.1 *Pretensioned members*—Losses for pretensioned members are classified as initial or long-term. One group of initial loss occurs during stressing and before transfer of prestress due to friction, seating losses, and temperature effects. It is the precaster's responsibility to understand the magnitude of these losses and account for them to provide the specified strand stress before transfer. Information on these types of losses is found in:

(a) Anchorage seating—4.2.1
(b) Form and abutment deformations—4.2.2
(c) Thermal effects—4.2.4
(d) Steel relaxation—4.2.5

Another initial loss is elastic shortening of the member that occurs at the time of transfer. As the prestress force is transferred to concrete, the member shortens. The steel and concrete are fully bonded, so the steel shortens with the concrete. This shortening causes a loss in stress in the prestressing steel, known as the elastic shortening loss, which should be accounted for by the designer. Long-term losses occur due to concrete creep and shrinkage and prestressing steel relaxation. Other changes of tendon force can occur due to temperature effects and external loads placed on the member at the time of casting or in service.

1.4.1.1 *Pretensioned members/lump sum method*—The lump sum method presented in Chapter 3 is often used for preliminary design. The values presented in sources referenced in Chapter 3 typically include all losses, both initial and long-term.

1.4.1.2 *Pretensioned members/simplified method*—The simplified method is a commonly employed approach to estimate prestress losses in typical pretensioned members. The designer needs to calculate four components of loss and add them together for the total prestress loss. Components and applicable sections are:

(a) Elastic shortening—4.3.2
(b) Creep—5.2
(c) Shrinkage—5.3
(d) Relaxation—5.4

1.4.1.3 *Pretensioned members/detailed method*—This guide provides information on more detailed methods of prestress loss estimation. Two alternate methods for a more detailed calculation of elastic shortening losses in pretensioned members are:

(a) Transformed section method—4.3.1
(b) Iterative gross section method with iteration—4.3.3

More detailed approaches to calculate long-term losses are presented in Chapter 6. These methods are used with a variety of creep and shrinkage models, as opposed to the simplified method, which uses a single model. Detailed methods also allow the designer to consider the influence of a cast-in-place composite deck if needed, whereas the simplified method only accounts for the weight of the deck, but not other factors such as differential shrinkage and internal stress redistributions between the beam and the deck, if acting compositely. The detailed methods are:

(a) AASHTO LRFD refined method (AASHTO 2012)—6.3.2
(b) General age-adjusted effective modulus method (Menn 1990)—6.3.3
(c) Incremental time-step method (Nilson 1987)—6.4

Chapter 6 (6.6) also provides information on the approximation of changes due to thermal effects of deck casting.

1.4.2 *Post-tensioned members*—Several approaches can be used to approximate prestress losses in post-tensioned members. Initial losses encompass all prestress loss during the stressing operation, including friction due to wobble and curvature, seating losses, and elastic shortening losses. The estimation of long-term losses for bonded post-tensioned members is essentially the same as for pretensioned members. Calculation of long-term losses in unbonded post-tensioned members is different, because losses are related to the overall change in tendon length, rather than the change in strain at a specific section.

1.4.2.1 *Post-tensioned members/lump sum method*—The lump sum method, presented in Chapter 3, is typically used only for preliminary designs. Before adopting a value for use in preliminary design, the licensed design professional should determine if the presented value includes friction and seating losses.

1.4.2.2 *Post-tensioned members/simplified method*—The simplified method can be used to estimate prestress losses in typical post-tensioned members. The designer needs to calculate five components of loss and add them together for the total prestress loss. Components and applicable sections are:

(a) Friction and seating loss—4.4
(b) Elastic shortening loss—4.5
(c) Creep loss—5.2.1 (bonded)
(d) Creep loss—5.2.2 (unbonded)
(e) Shrinkage loss—5.3
(f) Relaxation loss—5.4

Note that elastic shortening losses only occur in post-tensioned members with multiple tendons when the tendons are stressed sequentially. Tendons stressed first will incur losses as the concrete shortens due to the stressing of subsequent tendons.

1.4.2.3 *Post-tensioned members/detailed methods*—As with pretensioned members, long-term prestress loss in post-tensioned members are estimated using more detailed methods presented in Chapter 6, with a detailed description in 1.4.1.3. Initial losses are calculated per 4.3.3 and 4.4.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

a = constant
ab = eccentricity from the centroid of the beam (gross section) to the centroid of the deck (also centroid of the deck reinforcing steel), in. (mm)
A_c = area of concrete, in.^{2} (mm^2)
A_{comp} = transformed area of the composite section, in.^{2} (mm^2)
A_d = area of composite concrete deck, in.^{2} (mm^2)
A_g = area of gross concrete section at the cross section considered, in.^{2} (mm^2)
A_{ps} = area of prestressing steel, in.^{2} (mm^2)
A_{sd} = area of deck steel, in.^{2} (mm^2)
A_{tr} = transformed cross-sectional area, in.^{2} (mm^2)
$b(y)$ = width of cross-section at depth y relative to centroid of section, in. (mm)
C = factor in calculation of prestress loss due to relaxation according to the *PCI Design Handbook* (PCI 2010) method
C_c = creep coefficient
d = friction loss over length L, psi (MPa)
e = base of Naperian logarithms
e_b = basic elongation, in. (mm)
e_c = eccentricity of centroid of tendons with respect to the centroid of the gross cross section at the center of the beam, in. (mm)
e_d = distance between centroid of deck and centroid of composite beam, in. (mm)
e_e = eccentricity of centroid of tendons with respect to the centroid of the gross cross section at the ends of the beam, in. (mm)
e_p = eccentricity of centroid of tendons with respect to the centroid of the gross concrete at the cross section considered, in. (mm)
e_{pc} = eccentricity of centroid of tendons with respect to the centroid of the composite cross section, in. (mm)

e_{tr} = eccentricity of centroid of tendons with respect to the centroid of the f_{bpt} transformed concrete at the cross section considered, in. (mm)
$E(t)$ = modulus of elasticity at any time *t*, psi (MPa)
E_c = modulus of elasticity of concrete, psi (MPa)
E_c' = effective modulus of elasticity of concrete, psi (MPa)
E_c'' = age-adjusted effective modulus of elasticity of concrete, psi (MPa)
E_{cd} = modulus of elasticity of the composite deck, psi (MPa)
E_{ci} = modulus of elasticity of concrete at time of application of prestress, psi (MPa)
$E_c(t_i)$ = modulus of elasticity of concrete at time t_i, psi (MPa)
E_p = modulus of elasticity of the prestressing steel, psi (MPa)
f_{anchor} = strand stress at the anchorage device after seating, psi (MPa
f_c = concrete compressive stress, psi (MPa)
f_c' = specified compressive strength of concrete, psi (MPa)
f_{cd} = concrete stress at center of gravity of prestressing force due to all superimposed permanent loads that are applied to the member after it has been prestressed, psi (MPa)
f_{ci}' = specified compressive strength of concrete at transfer of prestress, psi (MPa)
f_{ci} = concrete compressive stress immediately after transfer at fiber under investigation, psi (MPa)
f_{cir} = net compressive concrete stress at center of gravity of prestressing force immediately after the prestress has been applied to the concrete, psi (MPa)
f_{cpa} = average compressive concrete stress at the center of gravity of the tendons immediately after the prestress has been applied to the concrete, psi (MPa)
f_{cps} = concrete stress at center of gravity of prestressing force due to all prestress and applied loads, psi (MPa)
f_{dead} = tendon stress at nonstressing end, psi (MPa)
f_{jack} = jacking stress, psi (MPa)
f_L = stress in prestressing steel at a distance *L* from jacking end, psi (MPa)
$f_{L/2}$ = stress in prestressing steel at a distance *L*/2 from the jacking end, psi (MPa)
f_{max} = maximum stress in the prestressing steel along the tendon length, psi (MPa)
f_{pbt} = stress in prestressing steel immediately before transfer, psi (MPa)
f_{pi} = prestressing steel stress immediately following transfer, psi (MPa)
f_{po} = prestressing steel stress after jacking and seating, psi (MPa)
$f_{ps}(t)$ = stress in prestressing steel at time *t*, psi (MPa)
f_{pt} = stress in prestressing steel immediately after transfer, psi (MPa)
f_{pu} = specified tensile strength of prestressing steel, psi (MPa)
f_{py} = specified yield strength of prestressing steel, psi (MPa)
f_x = stress in prestressing steel at a distance *x* from the jacking end, psi (MPa)
I_c = moment of inertia of the composite cross section, in.^{4} (mm^4)
I_d = moment of inertia of the deck, in.^{4} (mm^4)
I_g = moment of inertia of gross concrete section about centroidal axis, neglecting reinforcement, in.^{4} (mm^4)
I_{tr} = moment of inertia of transformed concrete section about centroidal axis, including reinforcement, in.^{4} (mm^4)
J = factor in calculation of prestress loss due to relaxation according to the *PCI Design Handbook* (PCI 2010) method
k = wobble friction coefficient per unit length of tendon, per ft (per m)
k_f = factor for the effect of concrete strength
k_{hc} = humidity factor for creep
k_s = factor for the effect of volume-to-surface ratio
k_{td} = time development factor
K_{cir} = modification factor in *PCI Design Handbook* (PCI 2010) method in calculation of concrete stress due to prestressing force immediately after the prestress has been applied to the concrete
K_{cr} = coefficient in the *PCI Design Handbook* (PCI 2010) method to account for loss due to creep
K_{df} = transformed section coefficient
K_{es} = factor in calculation of elastic shortening losses in Zia et al. (1979) method
K_{id} = section modification factor from AASHTO (2012) prestress loss method
K_{re} = factor in calculation of prestress loss due to relaxation in *PCI Design Handbook* (PCI 2010) method
K_{sh} = factor in calculation of prestress losses due to shrinkage in *PCI Design Handbook* (PCI 2010) method
L = strand length from anchorage to anchorage, ft or in. (m or mm)
L_{beam} = length of beam, ft or in. (m or mm)
L_{free} = length of strand outside of beam, ft or in. (m or mm)
M = bending moment experienced by cross section immediately after transfer (usually due to self-weight), in.-lb (N-mm)
M_b^o = initial creep-producing moment in the girder, in-lb (N-mm)
M_{deck} = moment in beam due to the weight of the deck, in.-lb (N-mm)
M_g = bending moment due to dead weight of prestressed member and any other permanent loads in place at the time of prestressing, in.-lb (N-mm)
M_{sd} = moment due to all superimposed permanent loads applied after prestressing, in.-lb (N-mm)
n_p = modular ratio; modulus of prestressing steel divided by modulus of concrete
N = number of sequentially stressed tendons
N_b^o = initial creep-producing force in the girder, lb (N)
P = applied tension force, lb (N)
P_{avg} = average force in the tendon, lb (N)
P_i = initial prestress force after anchorage seating loss, lb (N)