CE 414: Prestressed Concrete
Lecture 4
Prestress loss

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Contents

- Significance of prestress loss
- Elastic shortening
- Friction loss, relaxation of steel
- Loss due to anchorage take up

4-1 Significance of Loss of Prestress

In Chapter 1 the concept of calculating stresses in prestressed concrete members was developed, and it was pointed out that the distinctive feature of this structural system is that these stresses may be tailored to the desired level to assure satisfactory performance. We must again note that the prestress force used in making the stress computation will not remain constant with time. Stresses during various stages of loading (section 1-4) also vary since concrete strength and modulus of elasticity increase with time.

The total analysis and design of a prestressed concrete member will involve consideration of the effective force of the prestressed tendon at each significant stage of loading, together with appropriate material properties for that time in the life history of the structure. The most common stages to be checked for stresses and behavior are the following:

1. *Immediately following transfer* of prestress force to the concrete section stresses are evaluated as a measure of behavior. This check involves the highest force in the tendon acting on the concrete which may be well below its 28-day strength, f'_c. The ACI Code designates concrete strength as f'_{ci} at this initial stage and limits the allowable and concrete stresses accordingly.
2. *At service load* after all losses of prestress have occurred and a long-term effective prestress level has been reached, stresses are checked again as a measure of behavior and sometimes of strength. The effective steel stress, f_{se}, after losses is assumed for the tendon while the member carries the service live and dead loads. Also, the concrete strength is assumed to have increased to f'_c by this later time.

4-3 Elastic Shortening of Concrete

This section begins the consideration of losses by each individual source. Let us first consider pretensioned concrete. As the prestress is transferred to the concrete, the member shortens and the prestressed steel shortens with it. Hence there is a loss of prestress in the steel. Considering first only the axial shortening of concrete produced by prestressing (the effect of bending of concrete will be considered later), we have

$$\text{Unit shortening } \delta = \frac{f_c}{E_c} = \frac{F_0}{A_c E_c}$$

where F_0 is the total prestress just after transfer, that is, after the shortening has taken place. Loss of prestress in steel is

$$ES = \Delta f_s = E_s \delta = \frac{E_s F_0}{A_c E_c} = \frac{n F_0}{A_c} \quad (4\text{-}1)$$

EXAMPLE 4-1

A straight pretensioned concrete member 40 ft. long, with a cross section of 15 in. by 15 in., is concentrically prestressed with 1.2 sq. in. of steel wires which are anchored to the bulkheads with a stress of 150,000 psi (Fig. 4-1). If $E_{ci} = 4{,}800{,}000$ psi and $E_s = 29{,}000{,}000$ psi compute the loss of prestress due to the elastic shortening of concrete at the transfer of prestress. ($L = 12.2$ m, $E_{ci} = 33.1$ kN/mm^2, and $E_s = 200$ kN/mm^2)

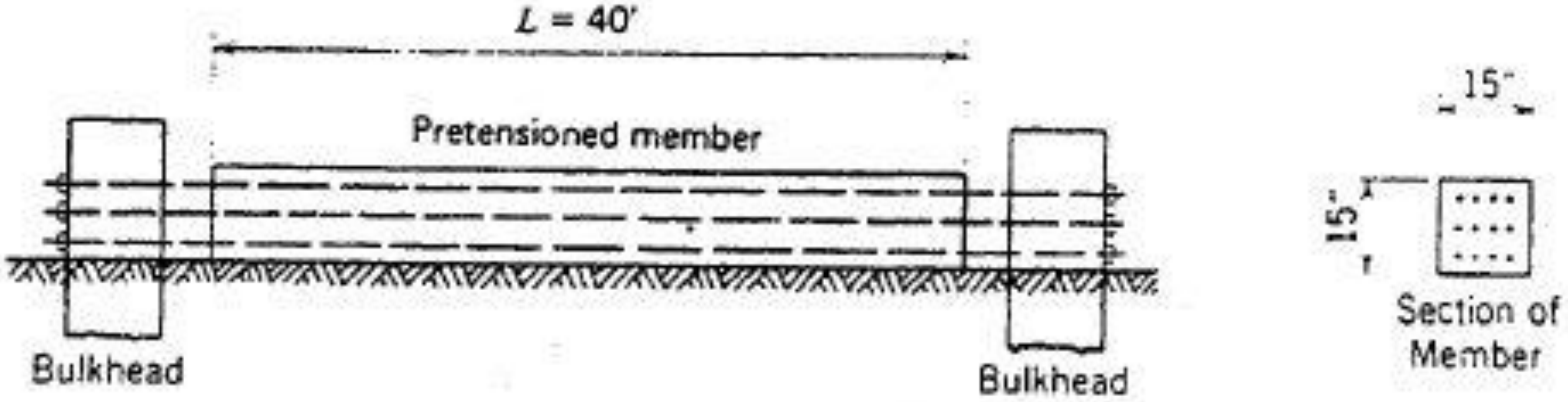

Fig. 4-1. Example 4-1.

Solution

$$F_i = 150{,}000 \times 1.2 = 180{,}000 \text{ lb}$$

(a) Using elastic analysis with transformed section estimate the change in steel stress at transfer:

$$ES = \Delta f_s = \frac{nF_i}{A_c + nA_s} = \frac{6 \times 180{,}000}{223.8 + 6 \times 1.2} = 4660 \text{ psi} \qquad (4\text{-}2)$$

$$\text{Steel stress} = 150{,}000 - 4660 = 145{,}340 \text{ psi}$$

(b) Using (4-4) with estimate of $F_0 \cong 0.9\ F_i$ we find $F_0 = (0.9)(180{,}000) = 162{,}000$ lb, thus for this member with $e = 0$ and $M_G = 0$:

$$ES = \Delta f_s = \frac{E_s}{E_{ci}}(f_{cir}) = n\frac{F_0}{A} = \frac{6 \times 162{,}000}{225} = 4320 \text{ psi} \qquad (4\text{-}5)$$

$$\text{Steel stress} = 150{,}000 - 4{,}320 = 145{,}680 \text{ psi}$$

EXAMPLE 4-2

Consider the same member as in example 4-1, but posttensioned instead of pretensioned. Assume that the 1.2 sq in. of steel is made up of 4 tendons with 0.3 sq in. per tendon. The tendons are tensioned one after another to the stress of 150,000 psi. Compute the loss of prestress due to the elastic shortening of concrete.

Solution The loss of prestress in the first tendon will be due to the shortening of concrete as caused by the prestress in the other 3 tendons. Although the prestress differs in the 3 tendons, it will be close enough to assume a value of 150,000 psi (1,034 N/mm^2) for them all. Hence the force causing the shortening is

$$3 \times 0.3 \times 150{,}000 = 135{,}000 \text{ lb } (600 \text{ kn})$$

The loss of prestress is given by formula 4-1

$$\Delta f_s = \frac{nF_0}{A_c} = \frac{6 \times 135{,}000}{225} = 3600 \text{ psi } (24.8 \text{ N/mm}^2)$$

Note that it is unnecessary to use the more exact formula 4.2.

Similarly, the loss due to elastic shortening in the second tendon is 2400 psi, in the third tendon 1200 psi, and the last tendon has no loss. The average loss for the 4 tendons will be

$$\frac{3600+2400+1200}{4}=1800 \text{ psi } (12.4 \text{ N/mm}^2)$$

indicating an average loss of prestress of 1800/150,000 = 1.2%, which can also be

obtained by using one-half of the loss of the first cable,

$$3600/2=1800 \text{ psi } (12.4 \text{ N/mm}^2)$$

The ACI-ASCE Recommendation for elastic losses accounts for the sequence of stressing effect on elastic losses, as illustrated in example 4-2, by modifying (4-5) as follows:

$$ES = K_{es} E_s \frac{f_{cir}}{E_{ci}} \tag{4-6}$$

where $K_{es} = 1.0$ for pretensioned members (example 4-1)

$K_{es} = 0.5$ for posttensioned members when tendons are in sequential order to the same tension

Note that in (4-4) for f_{cir} we modify the initial force to $F_0 = 0.9F_i$ for pretensioned members which have the immediate loss $ES = \Delta f_s$. Posttensioned

4-5 Loss Due to Creep of Concrete (CR)

The property of concrete to experience additional strain under a sustained load was described in Chapter 2. Figure 2-3, which shows the creep ratio variation with time, gives an idea of the nature of creep. The PCI Committee assumed that the percentage of creep with time is very similar to the average curve in this figure, but it is pointed out that considerable variation has been reported by different investigators. The upper and lower curves of Fig. 2-3 reflect this variation and serve to remind us that we are simply estimating the tendon stress loss due to creep, *CR*, not making a precise calculation.

Many factors affect the creep ratio. The PCI General Method has modifiers to attempt to take into account the following: volume-to-surface ratio, age of concrete at time of prestress, relative humidity, and type of concrete (lightweight or normal). The ACI-ASCE Committee approximates the most important of these as will be described below. The concrete stress at the level of steel is f_{cir} immediately after transfer as described in the previous section, (4-4). The beam responds elastically to the application of the prestress force at transfer, but creep of concrete will occur over a long period of time under a sustained load.

Creep is assumed to occur with the superimposed permanent dead load added to the member after it has been prestressed. Part of the initial compressive strain induced in the concrete immediately after transfer is reduced by the tensile strain resulting from the superimposed permanent dead load. Loss of prestress due to creep is computed for bonded members from the following expression (for normal weight concrete):

$$CR = K_{cr}\frac{E_s}{E_c}(f_{cir} - f_{cds}) \qquad (4\text{-}7)$$

where $K_{cr} = 2.0$ for pretensioned members

$K_{cr} = 1.6$ for posttensioned members

f_{cds} = stress in concrete at c.g.s. of tendons due to all super-imposed dead loads that are applied to the member after it is prestressed

E_s = modulus of elasticity of prestressing tendons

E_c = modulus of elasticity of concrete at 28 days, corresponding to f'_c

4-6 Loss Due to Shrinkage of Concrete

Shrinkage of concrete is influenced by many factors, as is creep, and our calculations for loss from this source will reflect those which are most important: volume-to-surface ratio, relative humidity, and time from end of moist curing to application of prestress. Since shrinkage is time dependent (see Fig. 2-4 for curve of shrinkage ratio versus time) we would not experience 100% of the ultimate loss for several years, but 80% will occur in the first year. As with creep, there is an upper and lower variation from the average shrinkage strain value, which is taken to be 550×10^{-6} in./in. The modifying factors for volume-to-surface ratio (V/S) and relative humidity (RH) are given below:

$$\epsilon_{sh} = 550 \times 10^{-6}\left(1 - 0.06\frac{V}{S}\right)(1.5 - 0.015RH)$$

$$= 8.2 \times 10^{-6}\left(1 - 0.06\frac{V}{S}\right)(100 - RH) \qquad (4\text{-}9)$$

The loss of prestress due to shrinkage is the product of the effective shrinkage, ϵ_{sh}, and the modulus of elasticity of prestressing steel. For some concrete, especially lightweight concrete, the basic ultimate shrinkage may be greater than the value used above. The only other factor in the shrinkage loss equation (4-10) is the coefficient K_{sh} which reflects the fact that the posttensioned members benefit from the shrinkage which occurs prior to the posttensioning (Table 4-4). This value will be 1.0 for pretensioned beams with very early transfer of prestress and bonded tendons, but for posttensioned beams we may have a significant reduction in shrinkage. For example, if posttensioning is done 5 days after completion of moist curing we have $K_{sh} = 0.80$, or only 80% of the shrinkage for a companion pretensioned beam.

$$SH = 8.2 \times 10^{-6} K_{sh} E_s\left(1 - 0.06\frac{V}{S}\right)(100 - RH) \qquad (4\text{-}10)$$

4-7 Loss Due to Steel Relaxation

Tests of prestressing steel[9] with constant elongation maintained over a period of time have shown that the prestress force will decrease gradually as shown in Fig. 4-2. The amount of the decrease depends on both time duration and the ratio f_{pi}/f_{py}. The loss of prestress force is called relaxation. It was shown in the tests that this source of loss is more significant than had been assumed prior to 1963. We can express this loss as follows:

$$\frac{f_p}{f_{pi}} = 1 - \frac{\log t}{10}\left(\frac{f_{pi}}{f_{py}} - 0.55\right) \tag{4-11}$$

With a time interval between the moment of stressing t_1 in the pretensioning bed (such as the one shown in Fig. 4-1) and a later time t when we wish to estimate the remaining force, we can write the following equation.

$$\frac{f_p}{f_{pi}} = 1 - \left(\frac{\log t - \log t_1}{10}\right)\left(\frac{f_{pi}}{f_{py}} - 0.55\right) \tag{4-12}$$

where log t is to the base of 10 and f_{pi}/f_{py} exceeds 0.55.[9]

4-8 Loss Due to Anchorage Take-Up

For most systems of posttensioning, when a tendon is tensioned to its full value, the jack is released and the prestress is transferred to the anchorage. The anchorage fixtures that are subject to stresses at this transfer will tend to deform, thus allowing the tendon to slacken slightly. Friction wedges employed to hold the wires will slip a little distance before the wires can be firmly gripped. The amount of slippage depends on the type of wedge and the stress in the wires, an average value being around 0.1 in. For direct bearing anchorages, the heads and nuts are subject to a slight deformation at the release of the jack. An average value for such deformations may be only about 0.03 in. If long shims are required to hold the elongated wires in place, there will be a deformation in the shims at transfer of prestress. As an example, a shim 1 ft long may deform 0.01 in.

A general formula for computing the loss of prestress due to anchorage deformation Δ_a is

$$ANC = \Delta f_s = \frac{\Delta_a E_s}{L} \tag{4-14}$$

Since this loss of prestress is caused by a fixed total amount of shortening, the percentage of loss is higher for short wires than for long ones. Hence it is quite difficult to tension short wires accurately, especially for systems of prestressing whose anchorage losses are relatively large. For example, the total elongation for a 10-ft (3.048 m) tendon at 150,000 psi (1,034 N/mm^2) is about

$$\frac{150{,}000 \times 10 \times 12}{30{,}000{,}000} = 0.6 \text{ in. } (15.24 \text{ mm})$$

and a loss of 0.1 in. (2.54 mm) would be a loss of 17% for (ANC). On the other hand, for a wire of 100 ft (30.48 m), an (ANC) loss of only 1.7% would be caused by such slippage, and it can be easily allowed for in the design, or counterbalanced by slight overtensioning.